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APPARATUS FOR COLLECTING WATER SAMPLES FROM DIFFERENT DEPTHS FOR BACTERIOLOGICAL ANALYSIS[1]

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Prerequisite to quantitative studies on the occurrence and importance of bacteria in the sea or other natural waters is a satisfactory device for collecting water samples for bacteriological analysis from any desired depth. Such a device must be easily sterilized, susceptible to aseptic manipulation under the most rigorous field conditions, possible to operate at high hydrostatic pressures and it must be made of biologically inert materials. It is desirable that the bacteriological water sampler can be used on the standard hydrographic or sounding wire in tandem or multiple units to provide for the simultaneous collection of samples from different depths and in conjunction with Nansen, Ekman, or Allen bottles, reversing thermometers or other hydrographic apparatus on the same wire. Sturdiness of construction, convenience of operation and economy of manufacture are also important features.

A survey of the literature reveals that more than a hundred bacteriological water samplers have been described introducing new

[1] Assistance in the preparation of these materials was furnished by the personnel of Work Projects Administration Official Project No. 65-1-07-2317.

[2] Contribution new series No. 150.

principles or modifications, but they all have limitations which restrict their usefulness. Unfortunately the data obtained from the bacteriological analysis of water collected with many samplers are open to criticism or are of only historical significance because the containers could not be sterilized, they were subjected to possibilities of extraneous contamination or they were made of metals which exert a bactericidal effect. The majority of the samplers which have been described are suitable only for collecting surface samples or samples from shallow depths. Others are unreliable, excessively expensive, intricately complicated or otherwise unsatisfactory. The apparatus which is described below has given good results under various conditions, it is simple to construct and it is positive in operation at any depth.

HISTORICAL

Besides the numerous methods which have been described for collecting water samples from the surface, three different types of samplers have been used: (1) weighted glass bottle from which the stopper is removed by a string, spring or messenger at the desired depth, (2) cylinder to which water is admitted by opening valves or by withdrawing a piston and (3) partially evacuated glass receptacle to which water is admitted by breaking a capillary glass tube.

Johnston (1892), Heydenreich (1899), Abbott (1921), Whipple (1927), Zillig (1929), Eyre (1930) and others have described ingenious devices for removing the stopper from a sterile bottle after it has been lowered into the water. However, it is obvious that the operation of such samplers is restricted to relatively shallow depths because the hydrostatic pressure at greater depths prevents the removal of stoppers from empty bottles. (The hydrostatic pressure of water increases approximately one atmosphere, or 15 lbs. per square inch, for each ten meters of depth.) In fact, unless provisions are made to prevent their descent, rubber stoppers will be pushed into the bottle at 50 to 100 meters and eschewing this, the empty bottles will be crushed at depths of a few hundred meters.

Otto and Neumann (1904) collected samples in a metal cylinder the ends of which could be closed with rubber gaskets at the desired depth. A nickel-plated cylinder with cocks operated by a messenger was used by Bertel (1911). However, it is objectionable to send such a cylinder down open because it might become contaminated with extraneous material while descending through the water and it is virtually impossible to perfect leak-proof valves or cocks which operate with sufficient ease to permit a pressure-resistant cylinder to be sent down empty. Matthews (1913) sought to obviate

this difficulty by filling a glass-lined cylinder with 95 per cent alcohol which provided for the sterility of the apparatus as well as for the equalization of pressure. One messenger was dropped to open the ends of the cylinder thus permitting the disinfectant to diffuse out, after which a second messenger closed the valves to entrap a water sample from the desired depth. Drew (1914) used this apparatus with expressed confidence to depths of 800 meters. Others have used it with phenol solution or other disinfectants. Besides the expense and inconvenience of operating this apparatus there is always a possibility of the disinfectant diffusing out prematurely through a faulty valve, or all of the disinfectant may not be washed out during the time the valves are opened and closed.

Young, Finn and Bedford (1931) fitted a phosphor-bronze cylinder with a brass piston which is withdrawn by a messenger-activated mechanism thereby aspirating a water sample. In order to eliminate the bactericidal effect of metals, Renn (unpublished) used a large ground-glass cylinder fitted with a solid ground-glass piston or plunger. It is doubtful, though, if such cylinder and piston arrangements can be made so that they are absolutely leak proof at great depths and it is especially difficult to exclude water from the orifice until the messenger is dropped. Unless it is closed right to the end, the orifice may admit a small amount of surface water which will be aspirated when the piston is withdrawn. This objection applies to Reyniers' (1932) glass cylinder which is ingeniously opened and closed by flexible rubber tubing.

Russell (1892) applied the unpublished evacuated glass-bulb capillary-tube idea of Massea by fitting a small flask with a glass tube the end of which was sealed hermetically. Provisions were made for breaking the end off the glass tube with a messenger thus permitting the ingress of water. Modifications of this capillary tube idea have been described, in most cases independently, by Praum (1901), Miquel and Cambier (1902), Portier and Richard (1906), Druse (1908), Parsons (1911) and Issatschenko (1914). In its most practical form Wilson (1920) used a large test tube fitted by means of a rubber stopper with a capillary glass tube the end of which is sheared off by a lever activated by a messenger. Gee (1932) attached it to an Ekman bottle, provided a long capillary tube to retard the sudden inrush of water when the tip was broken at great depths and used a thick-walled test tube with the neck constricted to prevent the descent of the rubber stopper into the test tube with increasing pressure. ZoBell and Feltham (1934) bent the glass inlet tube in such a way that it was broken at a point remote from pos-

sibilities of contamination by the messenger and simplified the breaking mechanism.

BACTERICIDAL EFFECT OF METALS

Alloys of copper, lead, nickel, silver, tin, zinc or other metals lend themselves readily to the manufacture of water sampling apparatus but it has been recognized for many years that all except the noblest metals have an oligodynamic effect (Raadsveld, 1934). After finding a reduction of 97 to 100 per cent in the bacterial population in 100 ml. quantities of sea water exposed to 2 square inches of bronze, nickel, brass and other alloys, Drew (1914) concluded that platinum is the only metal suitable for the interior of bacteriological water sampling apparatus. According to Bedford (1931) the bactericidal effect of the bronze and brass sampling bottle of Young et al. (1931) was inappreciable in sixty minutes but noticeable in ninety minutes.

Observations made at the S. I. O. during the last decade indicate that the less noble metals have a pronounced effect on the survival and activity of bacteria in samples of sea water. Under certain conditions most of the bacteria in sea water are killed within a few minutes when in contact with bright brass, bronze or other alloys containing copper, nickel, tin or zinc. Sea water itself stored in brass receptacles for a few hours becomes bacteriostatic for some bacteria although it enhances the growth of other bacteria. It is beyond the scope of this paper to consider the factors which influence the oligodynamic effect of heavy metals on the activity of bacteria in sea water but a few experiments will be summarized to show that metal containers for bacteriological water samples should be shunned.

Investigators on several oceanographic expeditions have analyzed bacteriologically water samples collected with Nansen, Ekman or other metal bottles. As a rule they observe that in spite of the fact that the bottles were not sterilized, few or no bacteria could be demonstrated in the water. Such observations have been interpreted as indicating that there are few or no bacteria in the sea. That such an interpretation is not always valid is proved by the data recorded in Table I which gives a protocol of a series of experiments in which sea water was stored in Nansen bottles.

Thoroughly cleaned Nansen bottles were filled with raw sea water. After different periods of storage at 22° C. samples were withdrawn for bacteriological analysis. Control water samples were stored in glass bottles for the same time. The bacterial population was

determined by plating procedures using nutrient sea water agar (ZoBell, 1941). It will be observed from Table I that whereas the

TABLE I—Number of Bacteria per Cubic Centimeter of Sea Water After Different Periods of Storage at 22° C. in Glass Bottles and in Brass Nansen Bottles

	Experiment 1		*Experiment 2*		*Experiment 3*		*Experiment 4*	
Period of Storage	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*	*Glass bottle*	*Nansen bottle*
0	94	—	108	—	143	—	294	—
1 hour	86	30	92	25	137	80	253	86
2 hours	72	21	102	18	89	26	222	19
3 hours	90	15	110	10	118	25	266	4
5 hours	52	0	76	3	226	1	207	0
24 hours	446	6	539	0	590	1	890	2

number of bacteria in the control sea water in glass containers decreased slightly with storage and then started to increase, the bacteria rapidly disappeared from the sea water which was stored in Nansen bottles for a few hours.

Only when collected from appreciable depths is there a likelihood of the water being in the Nansen bottle for an hour or longer. However, further experiments summarized in Table II indicate that many

TABLE II—Number of Viable Bacteria in Sea Water After Different Periods of Storage in Different Receptacles at 22° C., the Number Being Expressed as the Per Cent of the Original Number Present

Time in minutes	*Nansen bottle No. 3*	*Nansen bottle No. 13*	*Nansen bottle No. 18*	*Nansen bottle No. 19*	*Glass bottle control*
0	100	100	100	100	100
5	89	94	85	69	103
10	77	82	74	62	95
30	71	78	56	40	96
60	42	70	51	36	92

bacteria are killed or rendered incapable of multiplication in Nansen bottles within a few minutes. The average results of from three to six different experiments with four different Nansen bottles are given. Some of the Nansen bottles had a greater bacteriostatic effect than others, probably due to differences in the metallic surfaces which were exposed to the water samples. It is generally recognized that brightly polished metallic surfaces are more bacteriostatic than those which are coated with oxides or other film-forming substances.

GLASS BOTTLES

After trying different sizes and kinds of flasks, test tubes and bottles it was found that citrate of magnesia (CM) bottles with a one-hole rubber stopper substituted for the patented stopper, or ordinary pop or beer bottles are the best for collecting water samples. They are economical, rugged in construction, of sufficient volume and they stand erect on their flat bottoms without the need of special racks. Moreover, unlike the test tubes used by Wilson (1920), Gee (1932) and ZoBell and Feltham (1934) there is less tendency for the stoppers to be pushed in by the hydrostatic pressure. This can be prevented completely by inserting a piece of 8 mm. glass tubing of such a length that its ends rest upon the bottom of the bottle and the lower end of the stopper.

The use of the specially bent capillary inlet tubes as devised by various workers are somewhat difficult to construct and they are easily broken during sterilization, transportation or handling. The use of a piece of pressure rubber tubing, as used by Schach (1938), provides for flexibility and greatly simplifies the construction of the piece of glass that is broken at the time a sample is collected. Combining the most desirable features of the samplers of Schach (1938) and ZoBell and Feltham (1934), we have a device which is simple to construct and positive in action.

By means of a No. 1 one-hole rubber stopper a CM bottle is fitted with a four inch piece of 5 mm. glass tubing bent at right angles one inch from the end. The longer piece of the resulting L goes through the stopper into the bottle and the shorter arm is fitted with a four inch piece of ⅛ inch heavy-wall rubber pressure tubing. This part of the apparatus can be used over and over again almost indefinitely. The piece of projecting rubber tubing is fitted with a four inch length of 4 mm. glass tubing hermetically sealed at the outer end in a flame. The assembled apparatus is sterilized in the autoclave with the stopper resting loosely on the neck of the bottle held in place by the extruding glass tube. As soon as the bottles can be removed from the autoclave, preferably while they are still full of steam, the stoppers are firmly seated exercising aseptic precautions. When cool the bottles will be from 50 to 90 per cent evacuated.

To collect a sample of water the bottle is clamped into the brass carrier illustrated in Figure 37. The rubber tubing is bent around at an angle of 180° and held in this position by the spring clamp T. C. which is operated with the thumb. When lowered into the water to the desired depth the messenger is dropped. The glass tubing

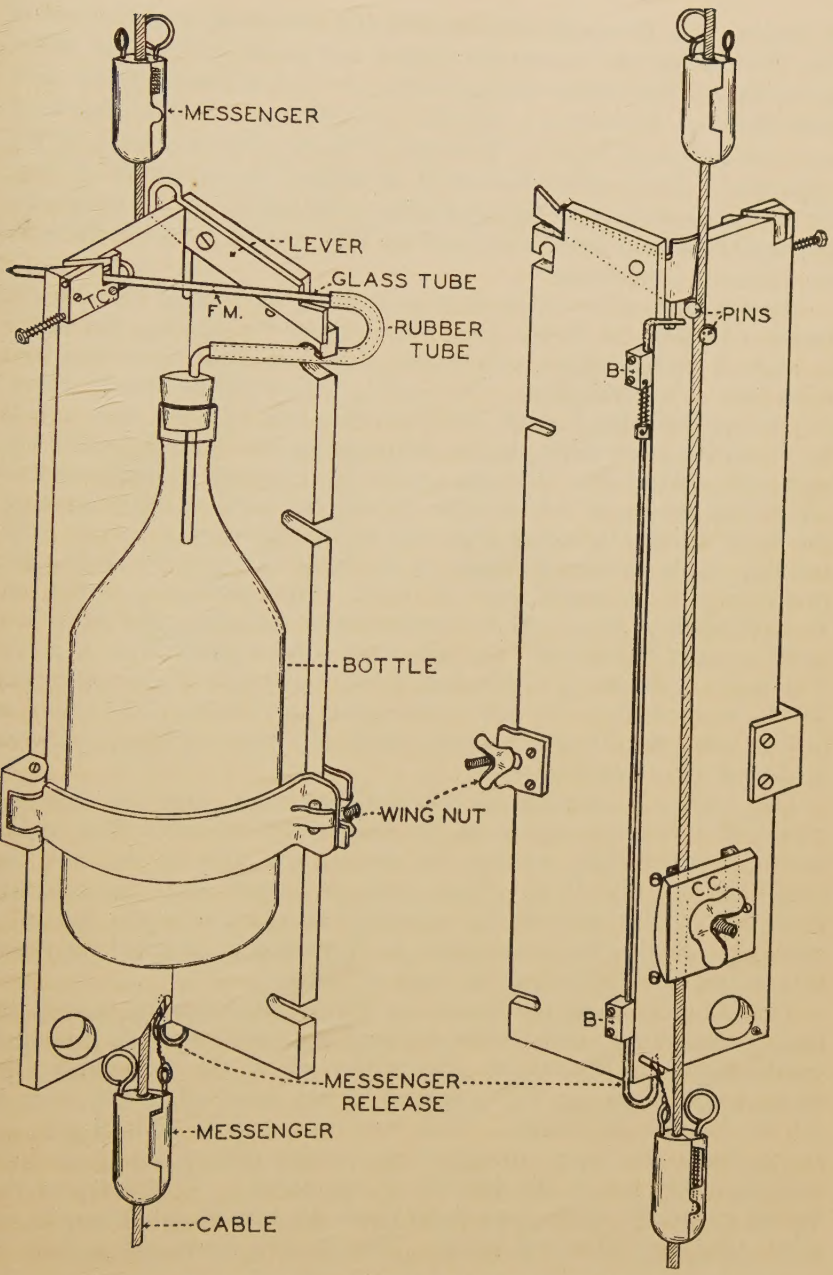

Figure 37. Front and back view of the J-Z bacteriological sampler.

is broken at a file mark midway between the clamp and the end of the lever when the messenger strikes the other end of the lever. Immediately the rubber tubing with the broken piece of the inlet tube flips out to assume a straight position again and a sample of water is aspirated three or four inches away from any part of the apparatus. Even at the instant it is broken the orifice is at least an inch from any part of the apparatus which might carry contaminating organisms, and there is no need for the operator to touch the inlet tube after it is sterilized.

The carrier is constructed of a piece of ¼ inch angle brass 2 × 2 inches wide and 11 inches long. The clamp for holding the bottle in place is made of a six inch length of ⅛ inch strap brass one inch wide bent in a semi-circle. One end is hinged to the carrier frame 4½ inches from the bottom and the other end is fitted with a bolt by which the brass strap can be tightened against bottles of different sizes with a wing-nut. A ⅛ inch notch ½ inch deep to accommodate the rubber tubing is cut over the top of the carrier, the bottom of the notch being 1½ inches from the top of the carrier frame. The notch is made somewhat larger at its inner end to help secure the rubber tube when pushed into the notch. The top corner is cut out as illustrated in Figure 38 to accommodate the inlet tube when the latter is bent into place. On the other side of the carrier a notch 3/16 inches wide and ¾ inches deep is cut at an angle of approximately 45° to accommodate the end of the glass inlet tube. The latter is held in place by the spring clamp made of a piece of brass rod bent U-shaped (T. C. in Figure 38).

The carrier is attached to the sounding wire, cable or rope by means of a wing-nut clamp on the back of the carrier. It is maintained in an upright position by placing the wire in the slot between the two pins P. P. When only one sample is to be collected there are simpler methods for attaching the carrier to the end of a rope, for example, but the sampler as illustrated is designed for rapid attachment to a hydrographic wire or cable.

The ⅛ inch brass rod shown in Figure 38 extending along the outer corner of the carrier is for releasing a messenger which is hooked on the bottom of the carrier. The upper end of the rod is bent over at an angle of 90° so it is engaged by the lever when the lever is hit by the first messenger. This forces the rod to slide down and in so doing the lower U-shaped end slides out of the 3/16 inch oblique notch cut in the bottom of the carrier. This releases the second messenger which then slides down the wire or cable to activate other apparatus attached below. The ⅛ inch brass rod is held in

position by the bearings BB. These are constructed from pieces of brass ¼ inches thick and ⅝ inches square. After drilling a ⅛ inch hole along the edge of them they are fastened in place with two ⅛ inch machine screws although they can be soldered to the carrier frame. The brass rod is held in position by means of a spring.

This device with the attached glass bottle has proved to be satisfactory for collecting water samples when used singly or on a line in combination with other apparatus in lakes as well as in the ocean.

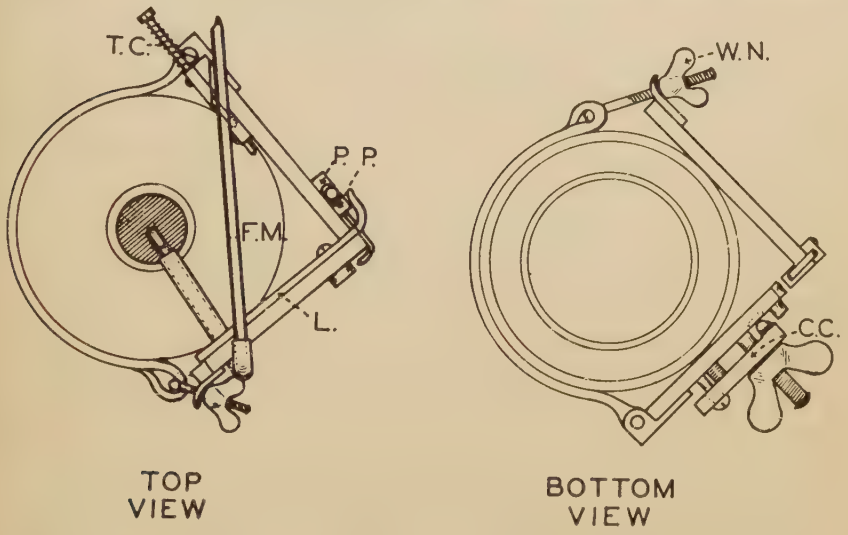

Figure 38. Top and bottom view of the J-Z bacteriological sampler with a citrate of magnesia bottle and its connections in place.

As many as eight of them fastened seriatum on the same line have made it possible to obtain samples from eight different depths in one cast. The repeated failure to recover test pigmented bacteria purposely applied to all parts of the carrier, the cable and the messenger proves that uncontaminated water samples can be collected under the most rigorous conditions. After a few words of instruction, uninitiated deck-hands and technicians alike can collect uncontaminated water samples with the apparatus suitable for bacteriological analysis.

In order to get a sample of water near the surface it is necessary to have the bottle partly evacuated. However, at depths exceeding 10 meters the bottle rapidly fills with water even if the bottle is not evacuated, the time required for the bottle to fill decreasing with

depth due to the increasing hydrostatic pressure. Once equilibrium has been established, which requires from two to ten minutes after the inlet tube is broken, there is no possibility of water from higher levels entering the bottle as it is pulled toward the surface because the pressure within the bottle is greater than that in the water at higher levels. Actually there is a slight tendency for water or air to be forced out of the bottle as it is raised. Sometimes when bottles fitted with small capillary tubes are hauled rapidly to the surface they appear with a fine jet of water being ejected.

Although the hydrostatic pressure aids in the collection of water samples, it prevents the apparatus from being used successfully at all depths. Some of the CM bottles will be crushed by the hydrostatic pressure at depths between 200 and 300 meters. The trial immersion of over a hundred stoppered CM bottles tied in groups on the submerged sounding line showed that 7 per cent of them were broken at 200 meters, 29 per cent at 300 meters, 81 per cent at 400 meters and all of them were broken at 600 meters. Although most water samples for bacteriological analysis are collected from the principal biotic zone which rarely exceeds 200 meters, in exploring the abyssal depths of the sea, it is desirable to have a bacteriological sampler which will function at depths exceeding 10,000 meters. Bacteriologists have been seeking such an apparatus for several years.

A PRESSURE RESISTANT BOTTLE

None of the so-called "deep sea" bacteriological water sampling bottles has been designed to function at depths exceeding a hundred meters or so, with the possible exception of those filled with a disinfectant (Matthews, 1913, Drew, 1914).

As mentioned above, valves and pistons on metal bottles are not leak-proof as far as bacteria are concerned. Evacuated glass bulbs which are large enough to collect a satisfactory sample are broken by the high hydrostatic pressure encountered at greater depths. The best high pressure bottle we could find without going to the expense of having special ones fabricated was a 125 ml. thick-walled flask with a round bottom supplied by the Corning Glass Company. It was cracked at a depth of 1200 meters.

While unquestionably glass bottles holding 100 ml. or more could be fabricated to tolerate any pressure in the sea, the cost is excessive and, moreover, it is doubtful if evacuated bottles should be used at great depths for collecting water samples for bacteriological analysis. When the capillary inlet tube on such a bottle is broken at a depth of 1000 meters, for example, the bacteria aspirated with the

water sample are subjected to an instantaneous pressure change of approximately 100 atmospheres, and correspondingly greater pressure changes at greater depths. The recovery of viable bacteria by Certes (1884), Carey and Waksman (1934) and others from depths near 5000 meters proves that neither the pressure encountered (approximately 500 atmospheres) nor its gradual release, effected by bringing the samples to the surface, killed all of the bacteria but it is indeterminate if some failed to survive this change. The work of Larsen et al. (1918) indicates that while certain bacteria tolerate pressures of 6000 atmospheres (about six times as high as any encountered in the sea), they are injured by the sudden release of pressures of 50 atmospheres or less depending upon the gas tension and other factors.

After experimenting with many types of devices to obviate the pressure factor for collecting samples at great depths, we have perfected the collapsible rubber bottle idea suggested to us by Dr. Austin Phelps of the Hopkins Marine Station. In its simplest form heavy rubber pear-shaped aspirator bulbs holding around 100 ml. are used (Figure 39). A 5 inch length of ⅛ inch heavy rubber pressure tubing is cemented in the 6 mm. opening of the rubber bulb with rubber cement. The rubber tubing is fitted with a 4 inch length of 4 mm. glass tubing with the outer end sealed in a flame, this part of the apparatus being the same as that used with the CM bottles described above.

The rubber bulbs can be sterilized in the autoclave after which the inlet tubes with the sealed ends are fitted aseptically with the bulb collapsed or depressed. At sea they can be sterilized by boiling, or in an emergency they can be sterilized by filling with 70 per cent alcohol or other disinfectant and then rinsed with sterile water after squeezing out the disinfectant, exercising aseptic technique. In practice we prepare and sterilize in convenient receptacles or paper-wrapped packets several hundred of the glass inlet tubes preparatory to embarking on a cruise. The rubber bulbs are sterilized by boiling or in a pressure cooker as needed, the bulbs being fitted with the glass inlet tubes while the former are still quite warm to lessen the likelihood of contamination and to get a better evacuation of the bulbs.

These rubber bulbs function in precisely the same way as the similarly fitted CM bottles. When the capillary inlet tube is broken by the lever activated by the messenger, the rubber bulb aspirates a water sample as it assumes its normal shape. It cannot be broken by the pressure regardless of whether it is collapsed or inflated

with air because as it is compressed by the increasing hydrostatic pressure, the pressure will always be nearly the same inside and outside the bulb due to the flexibility of the rubber. Consequently there is very little pressure change as the water sample is aspirated.

The rubber bulbs are secured to the same carrier as is used for the CM bottles by means of an auxiliary collar made of a 1¼ inch length of brass pipe 1⅛ inches in inside diameter. A hole is drilled ⅜ of an inch from the edge of the collar and threaded to take a ¼ inch machine screw 1¼ inches long having a knurled or wing-nut head. Two nuts are placed on the screw as illustrated in Figure 39 to keep the collar and attached rubber bulb in the proper position in the carrier. The collar is slipped over the neck of the sterilized pear-shaped bulb which is ready for use. Then the bulb is placed in position on the carrier and fastened there by slipping the screw projecting from the brass collar into a ¼ inch slot which is cut ¾ inches deep 4 inches from the top of the carrier. It is secured by tightening the machine screw and in so doing the end of the screw presses into the neck of the rubber bulb for about ⅛ inch thereby preventing the bulb from dropping out under any conditions. The collars are made detachable to facilitate handling the water samples collected in the rubber bulbs as well as to facilitate the sterilization of the latter and their assembly.

The trial immersion of the assembled rubber bulbs to depths exceeding 4000 meters without breaking the inlet tube proved that they were leak-proof. When the inlet tube was broken by the messenger-activated mechanism, the bulbs came up filled with water. Although we have not had an opportunity to send them down to the greatest depth in the sea, there seems to be no reason why they will not be just as efficient at 10,000 meters as at 4000 meters.

With the brass collar removed the rubber bulbs stand in an upright position on their flat bottoms. The sample can be transferred to a sterile glass container by squeezing the bulb, or aliquot portions can be removed as needed. The water samples should be stored in the refrigerator until they can be analyzed, although to insure reliable results the water should be analyzed for its bacterial population as soon as possible to minimize the changes which accompany the storage of water samples (ZoBell and Feltham, 1934, ZoBell and Anderson, 1938).

Since the rubber is not entirely inert the samples should not be left in the rubber bulb any longer than is necessary. There are certain bacteria found in the sea which slowly attack rubber as well as the synthetic products, neoprene and isoprene, as manifested by

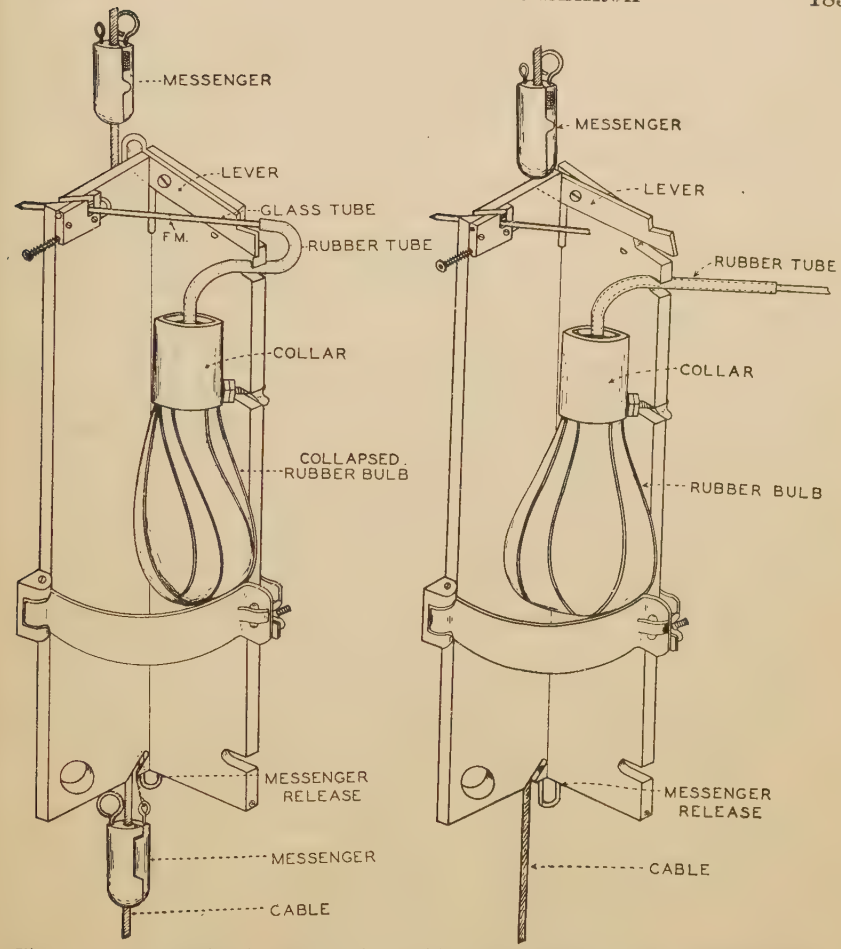

Figure 39. J-Z bacteriological sampler fitted with a pressure-resistant collapsible rubber bottle before and after collecting a sample of water. TC, thumb clamp, PP, pins for guiding cable; FM, file mark on glass inlet tube; L, lever which breaks tube; WN, wing nut on bottle clamp; CC, cable clamp for securing apparatus to cable.

oxygen consumption and the increasing bacterial population after several days. However, there is no evidence that the rubber is attacked for several days, so this possible source of error can be discounted provided the water samples are not left in the rubber bulbs for more than a few hours. The bacterial population and other properties of water samples of known bacterial content stored in rubber bulbs for 24 hours were not unlike those of water stored in glass receptacles under comparable conditions.

Several hundred water samples for bacteriological analysis have been collected from various depths in the sea proving the apparatus to be quite satisfactory. The sampler is known as the "J-Z" because of the activities of the S. I. O. mechanic, Carl I. Johnson, in perfecting the carrier.

Summary

None of the numerous samplers which have been described in the literature is entirely satisfactory for the collection of water samples for bacteriological analysis.

Containers made of copper, zinc, tin or nickel alloys are not suitable for the collection of samples of sea water for bacteriological analysis due to the inimical oligodynamic action of the metals. Many bacteria are killed and the sea water itself may be rendered bacteriostatic by exposure to the metals.

An apparatus is described which can be used on the standard hydrographic wire or cable for the collection of water samples aseptically from any desired depth in the sea. Multiple units provide for the simultaneous collection of samples from several different depths or the bacteriological sampler, known as the "J-Z", can be used in conjunction with other hydrographic sampling bottles and instruments. Glass bottles can be used to advantage for collecting samples at depths not exceeding 200 meters and collapsible rubber bottles are recommended for greater depths. High hydrostatic pressures do not interfere with the operation of the rubber bottles.

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PLANKTON PRODUCTION IN RELATION TO CHARACTER OF WATER IN THE OPEN PACIFIC

By

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INTRODUCTION

The dependence of the production of plankton upon an adequate supply of such inorganic salts as phosphates and nitrates in the photic zone is now an established planktological concept (Harvey, 1928; Ekman, 1935; Russell and Yonge, 1936). It is also well known that the photic zone often becomes depleted of such essential mineral substances and that when this occurs any increase in the total production of plankton will depend upon a renewal of these substances from some source. This source is usually the deeper water layers. In the open ocean the renewal must necessarily come from below. In high latitudes where vertical density gradients are not well developed and are eliminated in winter the renewal of the fertility of the photic zone is easily effected and the resultant production of plankton is often spectacular.

In the tropics and warm temperate latitudes a strong stratification of the water usually develops (Wüst, 1935, Sverdrup, 1938). This opposes any vertical mixing of the water so that a depletion or near depletion of nutrients in the photic zone results. Thus, the tropical plankton of the open ocean is characteristically extremely sparse as compared with that of the subpolar regions.

There is, however, no continuous increase in the total plankton from Equator to Pole. Certain regions of the tropical open ocean may be the seat of greater productivity. In a transect from Equator to Pole the region of least productivity may be the temperate regions rather than the tropical as is shown by the data presented in this report. This report is based on investigations made in the Pacific in 1929 on board the non-magnetic ship *Carnegie*[1] during the latter part of its last cruise.

[1] The *Carnegie* was built and operated by the Department of Terrestrial Magnetism of Carnegie Institution of Washington. Its last cruise (1928–29) terminated with destruction of the vessel by fire in Apia, Samoa, November 29, 1929.

METHODS

The biological program of the *Carnegie* included the collection of tow-net samples at 0, 50, and 100 meters, and the collection of quantitative samples with a Pettersson plankton-pump at the same levels. To augment these collections and to obtain a more complete picture of the quantity of plankton throughout the whole vertical extent of the upper layers vertical hauls were started at station 131, off San Francisco. These collections were continued on the cruise to Honolulu and along an indirect course from Honolulu to Samoa as shown in Figure 40. A vertical haul was made at each oceanographic station unless conditions prevented. Samples from the last two stations were lost. Twenty-five samples were available for study taken through the months of September to November, 1929. The net was one half meter in diameter constructed of no. 15 silk bolting cloth.

The net was dropped into the water and allowed to sink at an even rate of speed. About five minutes elapsed for the net to reach 150 meters depth when it was immediately hauled in at the same rate at which it was lowered. The line to which the net was attached was weighted but the net was not. Consequently, the net fished on both the downward and the return trips. The net did not tow any appreciable length of time at its lowest level. The samples were preserved in formaldehyde.

When this part of the biological program was started the vertical hauls were made from 150 meters depth. Later, beginning with station 154, the hauls were taken from 100 meters depth in order to restrict them to levels being investigated by other methods. A factor of 1.5 was applied to the plankton values for stations 154 to 160 in order to make them more comparable to the values for the other stations.

For the determination of the relative quantity of plankton in each catch, the samples were dried to constant weight in an oven at a temperature of 100° C. The dry weight was taken as an expression of the relative quantity of plankton in the upper 150 meters. Weighings were made to the nearest 10 milligrams.

At each oceanographic station water samples were analyzed for salinity, dissolved oxygen, and phosphate. In the upper levels samples were collected at approximately 0, 5, 25, 50, and 100 meters. Temperatures were taken at the same levels. The values used in the present study represent means for the column of water extending from the surface to 100 meters computed from the formula

$$M = (a + 2b + 2c + 2d + e)/8$$

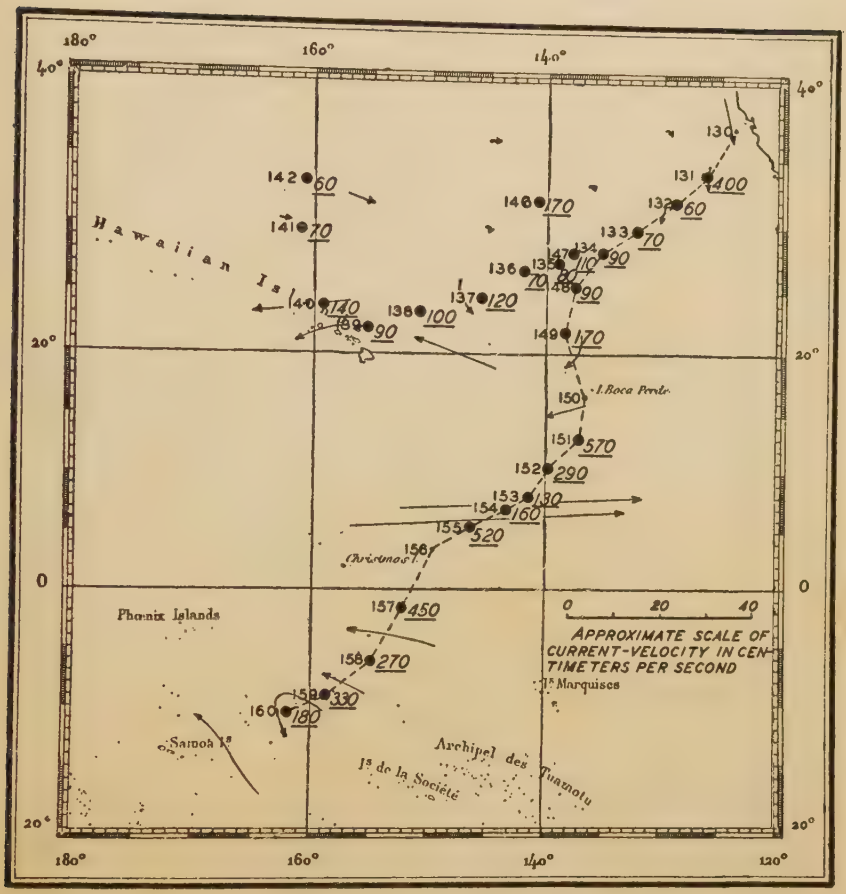

Figure 40. Distribution of *Carnegie* vertical-haul stations. Small numbers indicate station number. Large italicized numbers give dry weight of sample in milligrams. Dotted line joins stations used in graphs of Figure 41. Arrows indicate direction and magnitude of currents for the 100-meter level, relative to assumed zero current at a depth of 2,000 meters according to *Carnegie* dynamic computations.

where *a*, *b*, *c*, etc., are values for 25-meter intervals from the surface to 100 meters scaled from graphs of the data. Means for the 100 meter rather than the 150 meter column were used since it is probable that the characteristics of the upper 100 meters are much more important in total plankton production than conditions below that level.

RESULTS

The plankton weights and the means for various physical and chemical factors for the upper 100 meters are shown in Table I for all the *Carnegie* stations at which vertical hauls were made. The results for stations in a more or less direct line from San Francisco to

TABLE I—Dry Weights of Vertical-haul Plankton Samples and Mean Values of Temperature, Salinity, Phosphate, and Dissolved Oxygen for the Upper 100 Meters, *Carnegie* Stations 130 to 160

Station No.	*Dry weight of sample*[1] *milligrams*	*Depth of haul meters*	*Temperature °C*	*Salinity per mille*	*Phosphate PO_4 mg/m³*	*Oxygen saturation per cent*
130	...	...	12.30	33.51	97	86
131	400	150	15.04	33.31	..	100
132	60	150	17.74	33.70	16	101
133	70	150	20.75	34.74	7	100
134	90	150	20.37	34.61	6	100
135	80	150	21.57	35.06	5	106
136	70	150	21.79	35.19	3	100
137	120	150	23.91	35.01	4	99
138	100	150	24.69	34.79	4	96
139	90	150	25.30	34.93	6	98
140	140	150	26.71	35.00	7	96
141	70	150	23.95	35.18	5	99
142	60	150	20.86	34.70	6	100
146	170	150	22.02	34.76	6	99
147	110	150	21.98	35.20	6	100
148	90	150	22.20	35.07	..	97
149	170	150	22.52	35.02	6	99
150	...	...	22.86	34.68	10	96
151	570	150	18.39	34.44	..	63
152	290	150	16.61	34.48	53	36
153	130	150	27.06	34.45	12	90
154	160	100	27.79	34.40	9	92
155	520	100	27.58	34.96	32	94
156	...	...	27.03	35.04	42	95
157	450	100	27.03	35.28	59	94
158	270	100	28.08	35.64	48	75
159	330	100	28.45	35.74	16	89
160	180	100	28.47	35.64	14	87

[1] Values for stations 154 to 160 have been adjusted by factor 1.5.

Samoa are presented in graphs in Figure 41. These stations are joined by a dotted line in Figure 40.

At station 131 there was a heavy production of diatoms. The sample consisted almost entirely of *Rhizosolenia semispina* Hensen. None of the other samples showed any indication of blooms or swarms of any organism such as occurs in pulses in northern waters in the spring and fall. The samples contained both plants and animals, mostly diatoms, copepods, and chaetognaths.

The weights of the 150-meter hauls varied from 60 to 570 milligrams; of the 100-meter hauls from 110 to 350 milligrams. The adjusted weights for the latter varied from 160 to 520 milligrams. The sample from station 151 was not quite comparable as it contained a large colony of salps. That this colony was not representative is indicated by the fact that no salps were taken with the tow nets at that station. Omitting that sample the largest value obtained was from station 155 with an adjusted weight of 520 milligrams.

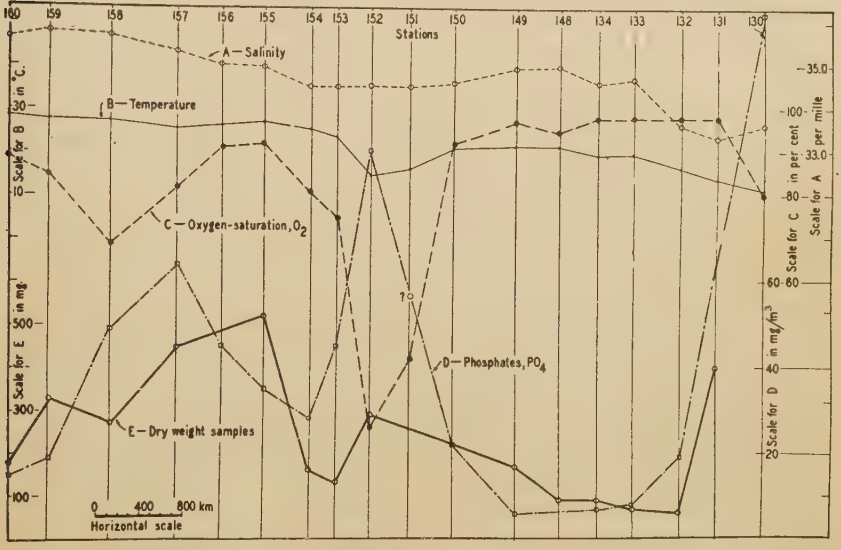
160 159 158 157 156 155 154 153 152 151 150 149 148 134 133 132 131 130
Stations
A—Salinity
B—Temperature
C—Oxygen-saturation, O_2
D—Phosphates, PO_4
E—Dry weight samples
Scale for B in °C.
Scale for E in mg
Scale for C in per cent
Scale for A per mille
Scale for D in mg/m³
0 400 800 km
Horizontal scale

Figure 41. Graphs showing weights of plankton samples and mean values of phosphate, oxygen, temperature, and salinity between San Francisco and Samoa.

The stations north of 20° north generally had less plankton than those south of that latitude. The average weight of the 16 samples in the north was 120 milligrams (Table II). Only 7 of the samples weighed over 100 milligrams and only one over 200 milligrams. The average weight of 8 samples taken in the tropics was 291 milligrams. All tropical samples were over 100 milligrams and 6 were over 200 milligrams. Thus, there was a distinctly greater production of plankton in the tropics than at the more northern latitudes. This picture of greater productivity in the tropics does not depend upon the adjustment of the 100 meter values for stations 154 to 160. The mean of the uncorrected values is 210 milligrams, 90 milligrams above the mean for the more northern stations.

The difference in productivity of the two regions is correlated with differences in phosphate concentration. This is in accord with the results of most planktological investigations. The more northern stations, 131 to 149, were in water rather depleted of phosphate while the southern stations, 150 to 160, were in much richer water (Table I). The mean of phosphate values for the 14 northern stations for which there are data was 6 milligrams while for the 10 southern stations the mean was 30 milligrams (Table II).

TABLE II—Mean Weights of Plankton in the Upper 150 Meters and Environmental Conditions in the Upper 100 Meters

	Dry weight of plankton samples	*Temperature*	*Salinity*	*Phosphate PO_4*	*Oxygen saturation*
	milligrams	*°C*	*per mille*	*mg/m³*	*per cent*
Sixteen stations north of 20° north	120	21.96	34.76	6	99
Eleven stations south of 20° north	291	23.10	34.98	30	83

The correlation between plankton and temperature is also interesting. Planktologists are accustomed to associating plankton rich (eutrophic) water with cold water (Peters, 1934; Ekman, 1935). The mean temperature for the 16 *Carnegie* stations north of 20° north was 21.96° C. while for the tropical stations 23.10° C. The most productive of the two general regions, then, was the warmer one. However, as is pointed out below, this correlation is reversed in a station to station comparison of results.

A comparison of the oxygen concentrations in the two regions shows that the northern waters which have lower temperatures and less phosphate are more nearly saturated with dissolved oxygen (Table II). The mean for 16 northern stations was 99 per cent of saturation while for 11 tropical stations 83 per cent.

Variations in salinity show no correlation with variations in plankton content. The average salinity of 16 northern stations was 34.76; of 11 tropical stations 34.98‰.

The greater productivity of the tropical regions of the open ocean as compared with latitudes between 20° and 34° in the North Pacific is probably a result of disturbed hydrographic conditions in the tropical waters. The region of the equatorial currents is marked by indications of vertical water movements (Sverdrup, et al; in press; chap. 15).

The above data suggest that plankton production in the open Pacific is dependent upon unstable dynamic conditions. Sverdrup and

Allen (1940) stressed the importance of the "age" of the different water masses supporting plankton populations off the coast of southern California. In connection with the ability of the water to support plankton, the terms "old water" and "new water" may be useful in describing the different water masses of the open Pacific. The warm Pacific characteristically has "old water" at the surface; water which supports a sparse plankton population. However, where there are diverging currents, such as the Equatorial and California Currents, upwelling subsurface water is brought to the surface. The resultant surface water is relatively new or eutrophic water and supports a heavier plankton production.

The dependence of plankton production upon disturbed hydrographic conditions in the regions investigated is brought out further if we examine the *Carnegie* data along a line from San Francisco to Samoa (Figure 41). At station 130 off California there was a very high phosphate content accompanied by low temperature and salinity. These conditions are characteristic of the California Current in which the station was located. Unfortunately no vertical haul was made at this station. At station 131 the phosphate content was still high and the temperature and salinity low, probably due to the influence of the California Current. The plankton sample from this station weighed 400 milligrams and consisted mostly of diatoms. The oxygen content at this station was higher than that in the California Current. This probably was due to the activity of the rich phytoplankton which resulted from the rich nutrients in the water derived from the above current.

From stations 132 to 149 inclusive there was evidently little mixing between waters of the surface layers and those below; the surface layer was composed of "old water." The phosphate content was low and oxygen concentration high; temperatures and salinities were high. Plankton production was low; sample weights were all under 200 milligrams.

Stations 150 to 152 inclusive were in the North and Counter Equatorial Currents. The hydrographic conditions there indicate strong vertical water movements (Sverdrup, et al). The upper layers have characteristics of "new water." The mean phosphate content of the upper 100 meters was remarkably high while the oxygen, temperature, and salinity were definitely lower. The plankton values were higher than farther northward, namely, 290 milligrams (not considering station 151 with 570 milligrams). This higher production of plankton occurred in spite of a surface layer of light water 75 meters deep which did not have any deep-water characteristics and

was depleted of nutrients. This stratification is not brought out in the 100 meter means but is evident in the vertical curves for the various factors (unpublished *Carnegie* data). Most of the production in this region probably occurred just below the 75 meter level.

At stations 153 and 154, in the Counter Equatorial Current, there was a return to "old water" conditions in the upper 100 meters and the plankton weights dropped to 130 and 160 milligrams.

From stations 155 to 158 inclusive, mostly in the South Equatorial Current, the 100 meter layer was again characterized by conditions which indicate mixing with deeper water although not of such a decided character as in the North Equatorial Current. The phosphate values were high and the oxygen low. The means for temperature and salinity do not show any appreciable indication of the influence of deeper water, but this, again, is brought out in the curves of the vertical distribution of these factors. In this region the weights of the samples were comparatively high, between 270 and 520 milligrams.

Stations 159 and 160 probably represent a transition to another region of more stable conditions with high oxygen and low phosphate concentrations. The weights of the samples were 330 and 180 milligrams.

SUMMARY

1. In the open Pacific Ocean from September to November, 1929 there was a greater production of total plankton in the tropics between latitudes 20° north and 11° south than between latitudes 20° and 34° north.

2. There was a positive correlation between the density of plankton in the upper 150 meters and the phosphate content of the water in the upper 100 meters.

3. The water richer in phosphate and plankton occurred in regions where there were indications that some form of vertical circulation was transporting phosphate from the reservoirs below to the upper layers. These regions were in (a) the California Current and its outflow, (b) the North Equatorial Current and northern edge of the Counter Equatorial Current, and (c) the northern part of the South Equatorial Current.

4. Plankton production is not a function of latitude but depends upon the presence of "new water" high in nutrient salts. Although characteristic of high latitudes, "new water" may form in regions of relatively high temperature as well and result in increased plankton production.

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TRANSPORT OF THE FLORIDA CURRENT OFF HABANA

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INTRODUCTION

This report is an analysis of four *Atlantis* sections across the Florida Current in the locality between Key West and Habana. In particular the volume transport of the current is calculated from the mass distribution observed on these four sections. The assumptions for the calculations are critically discussed, making use of records of sea level at Key West.

The first section, 4 March 1934 (stations 2003–2008), was made during Cruise 25 under the leadership of Dr. A. E. Parr (*Bulletin Hydrographique pour l'année 1934,* pp. 45, 111). The second section, 19–20 February (stations 2343–2347), and third section, 12–13 April 1935 (stations 2434–2438), were made during Cruise 41 by Dr. Parr and by Mr. Y. H. Olsen respectively (*Bulletin Hydrographique pour l'année 1935,* pp. 51, 100, 102). The fourth section, 24–25 March 1938 (stations 3006–3012), was made during Cruise 74 by Mr. Alfred H. Woodcock.

This region of the Straits of Florida had been investigated during February–May 1887 by Pillsbury (1887, 1890), who carried out extensive current measurements down to 130 fathoms from the *Blake* at anchor. A section of temperature by means of reversing thermometers and of salinity was made from the *Bache* in March 1914 (Bigelow, 1915).[2] Wüst (1924) attempted a dynamic calculation from the *Bache* material, but found the observations insufficient. *Dana* stations 1224–1229 were made in this region in February 1922,

[1] Contribution No. 303.

[2] In May 1878 the temperature at a number of points between surface and bottom for five stations on this section of the Straits had been determined from the *Blake* (Agassiz, 1888, Fig. 157). Within a few years of the same time another temperature section from the *Blake* was made farther west, approximately along the 84th meridian, but the date is not stated (Lindenkohl, 1895, Diagram No. 4).

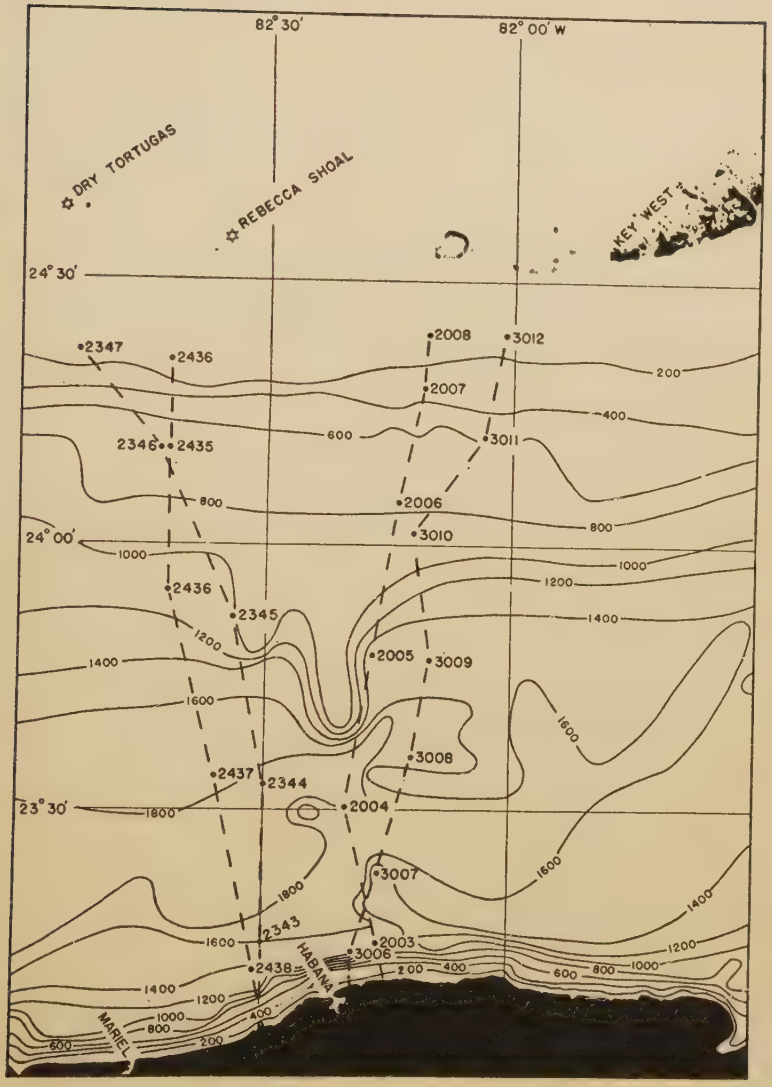

Figure 42. Station positions for the four *Atlantis* sections near Habana in the Straits of Florida. Isobaths are shown for each 200 meters.

three of them forming a section across the Straits (Schmidt, 1929).[3] In February 1932 a section consisting of *Mabel Taylor* stations 401–406 was made by Parr (1935). Parr shows temperature and salinity cross-sections for the *Dana* and *Mabel Taylor* sections and for the first *Atlantis* section, March 1934, and temperature-salinity curves for these as well as the *Bache* section. He discusses the origin of the waters found in these sections and finds them to be largely unadulterated Caribbean water but partly, especially in the northern part of the surface layers, of Gulf of Mexico origin.

The *Dana* and *Mabel Taylor* sections are not suitable for inclusion in this study. In neither case were unprotected thermometers used in determining the sampling depths. Furthermore the former consists of only three stations, while on the latter section the southernmost station lies 12 miles from the Cuban shore, so both are definitely less complete than the *Atlantis* sections.

METHOD

The positions of the stations are shown in Figure 42. The isobaths on this chart were constructed from the soundings entered on U. S. Coast and Geodetic Survey Chart No. 1113 (United States—Gulf Coast, Habana to Tampa Bay, March 1933, reissued July 1938). The soundings are so sparse that the contours are not at all reliable. No adequate sounding survey has been made of any part of the Straits of Florida except the shallow coastal areas. This imposes a severe restriction on studies of the flow through the Straits.

The anomaly of specific volume (0° C and salinity 35 per mille as standard) was computed from the observed temperature, salinity and depth for each sample by Sverdrup's (1933) tables. The complete data and computed values for observed depths are given for the fourth section in Table I. Since temperature, salinity and oxygen values for the first three sections have already been published these sections are not repeated here in tabular form.

Anomaly of specific volume was plotted against depth and a smooth curve drawn for each station. The depths of chosen standard values of anomaly of specific volume were determined from these curves and then entered on the cross-sections, and finally the isopleths of anomaly of specific volume were drawn, giving Figures 43–46. Few of the stations reach near the bottom, so considerable uncertainty was involved in extrapolating the isopleths to the walls of the Straits.

[3] The temperature and salinity cross-section is shown by Nielsen (1925, Fig. 2). See also Jacobsen (1929).

Smooth salinity-depth curves were constructed for each station, from which the depths of 36.4 and 36.6 per mille were determined and entered on the cross-sections. On this basis the areas of the salinity maximum are indicated in Figures 43–46. These may be correct in their broadest features, but the sampling in the upper 300 meters was too coarse to define clearly the thin layer of high salinity, which occurs near the depth of maximum stability.

In order to integrate the hydrostatic equation the station curves of anomaly of specific volume were extended where necessary to 1200 meters, or to the bottom at shallower stations, by use of the isopleths on the cross-sections. Likewise smooth curves of anomaly of specific volume versus depth have been drawn for both walls of each section. By integrating along these curves, using depth in meters to represent pressure in decibars, the anomaly of geopotential above 1200 db was found for the intersections of each station vertical and of the walls with the standard isopleths of anomaly of specific volume and with the sea surface. The resulting values for the sea surface at the northernmost station and at the Cuban shore are given in Table II. The acceleration potential (Montgomery, 1937; Montgomery and Spilhaus, 1941),

$$\Upsilon = \Phi_a + \delta p$$

(where Φ_a is anomaly of geopotential, δ is anomaly of specific volume and p is pressure), was found for all the intersections.

The volume transport through an area bounded by two successive station verticals (or the wall and adjacent station) was found from the expression

$$\Delta V = \frac{\Delta \Upsilon \Delta z}{f} .$$

Here Δz is the average distance between the two isopleths, f is the Coriolis parameter computed for the mid-latitude of each pair of stations, and $\Delta \Upsilon$ is the average, for the two isopleths, of the difference in acceleration potential between the two verticals. The sums for each complete layer and for each section are given in Table III. The transport through the small area lying north of the northernmost station was neglected in each case.

As a check, the total transport for each section was also computed directly from the expression

$$V = \frac{1}{f}\left[\int_{\text{right}} \Phi_a \, dz \; - \int_{\text{left}} \Phi_a \, dz\right]$$

TABLE I—*Atlantis* Habana Section, 24–25 March 1938

Station	*Depth* (*meters*)	*t* °C	*S* °/₀₀	σ_t *g* l^{-1}	δ *cl ton*$^{-1}$
3006, 24 III 38	1	26.03	35.79	23.64	427
1715–1820	24	25.97	35.90	23.74	418
23° 14′ N, 82° 19′ W	47	25.90	35.91	23.77	416
Depth 1463–1372 meters	94	25.60	36.00	23.94	402
Wind force 3	141	23.85	36.58	24.90	312
	188	20.92	36.74	25.86	222
	282	17.77	36.45	26.46	168
	376	14.29	35.84	26.79	138
	470	11.21	35.35	27.03	115
	564	9.09	35.07	27.175	102
	752	6.59	34.87	27.39	81
	938*	5.38	34.90	27.575	64
	1128	4.59	34.94	27.70	53
3007, 24 III 38	1	26.01	35.91	23.74	417
1935–2140	44	25.96	35.91	23.75	418
23° 23′ N, 82° 16′ W	82	25.71	36.00	23.905	405
Depth 1710 meters†	119	23.61	35.97	24.51	348
Wind force 3	157	19.91	35.93	25.52	253
	233	18.29	36.47	26.34	178
	308	14.66	35.97	26.81	134
	383*	12.77	35.62	26.94	123
	446	11.12	35.35	27.05	113
	572	8.11	34.96	27.24	95
	699	6.51	34.87	27.40	79.5
	825*	5.53	34.87	27.53	67
	1099*	4.34	34.97	27.75	47
3008, 24–25 III 38	1	25.90	35.93	23.79	412
2255–0105	38	25.92	35.93	23.78	415
23° 36′ N, 82° 12′ W	66	24.25	36.00	24.35	361.5
Depth 1701 meters	89	21.25	35.95	25.16	285
Wind force 2	114	19.62	35.93	25.59	245
	165	18.60	36.38	26.20	189
	216	16.20	36.13	26.59	153
	267*	14.51	35.86	26.76	138
	302	13.15	35.66	26.89	126
	371	10.72	35.28	27.06	110
	440	9.18	35.07	27.16	101
	509*	8.05	34.96	27.25	92.5
	640*	6.31	34.88	27.44	75

TABLE I—*Cont.*

Station	*Depth* (*meters*)	*t* ° *C*	*S* °/₀₀	σ_t *g* l^{-1}	δ *cl* ton^{-1}
3009, 25 III 38	1	24.99	36.06	24.16	377
0245–0358	49	21.42	36.36	25.44	257
23° 47′ N, 82° 10′ W	97	19.72	36.35	25.88	217
Depth 1508 meters	144	17.35	36.29	26.44	165
Wind force 2	191	15.34	36.04	26.71	140
	286	11.64	35.44	27.015	113
	381	8.59	35.01	27.215	94
	476*	7.28	34.90	27.32	84
	570	6.36	34.88	27.43	75
	779	5.05	34.92	27.625	57
	987	4.59	34.94	27.70	51
	1196*	4.26	34.96	27.74	49
	1389*	4.14	34.99	27.785	46
3010, 25 III 38	1	24.77	36.04	24.21	372
0530–0620	25	23.58	36.33	24.79	318
24° 01.5′ N, 82° 12′ W	50	20.95	36.33	25.54	247.5
Depth 878 meters	100	18.73	36.36	26.15	191
Wind force 1	150	15.88	36 08	26.615	148
	199	13.53	35.71	26.85	127
	298	10.19	35.21	27.11	103
	397*	8.09	34.96	27.245	91
	495	6.84	34.87	27.36	81
	594	5.98	35.01‡	27.59	59.5
	793*	.06	34.90	27.61	59
3011, 25 III 38	1	24.55	36.10	24.33	361
0830–0915	25	23.51	36.31	24.79	318
24° 12.5′ N, 82° 03.5′ W	50	20.77	36.36	25.62	240
Depth 539 meters	100	17.15	36.27	26.47	161
Wind force 2	149	14.65	35.91	26.77	133
	198	12.70	35.61	26.94	118
	297	10.47	35.28	27.10	104
	395*	9.18	35.08	27.17	99
	493	7.81	34.94	27.28	89
3012, 25 III 38	1	24.33	36.27	24.52	343
1030–1055	25	21.32	36.38	25.47	253
24° 24′ N, 82° 01′ W	50	19.80	36.31	25.83	220
Depth 161 meters	75	18.50	36.36	26.21	185
Wind force 2	100	15.62	36.08	26.67	141.5
	150	11.57	35.41	27.01	109.5

* Depth determined with unprotected reversing thermometer.

† At this position Chart No. 1113 shows sounding of 710 fathoms or 1300 meters.

‡ Looks very doubtful on $\sigma_t - S$ diagram, so this observation has been omitted from consideration.

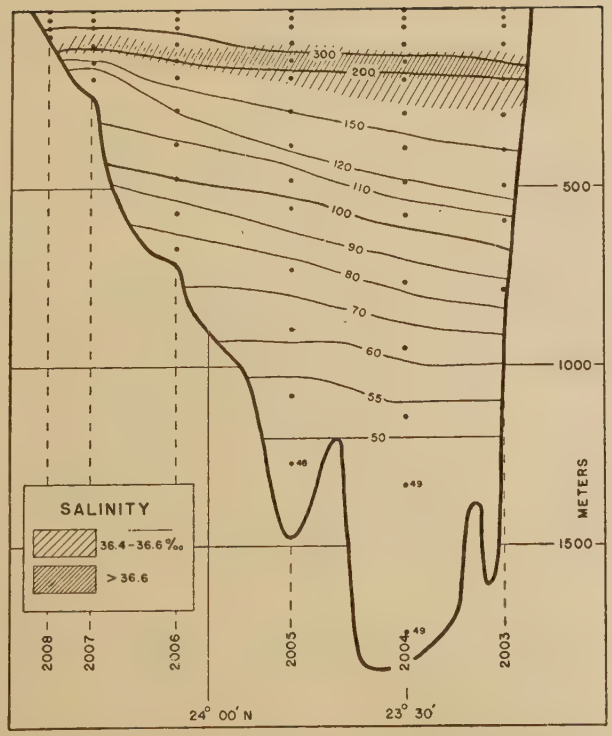

Figure 43. *Atlantis* Habana section on 4 March 1934 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

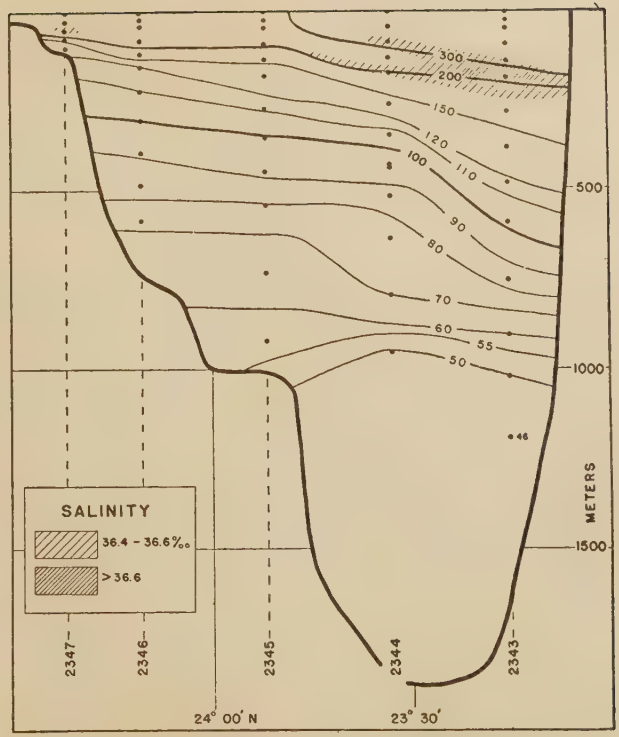

Figure 44. *Atlantis* Habana section on 19–20 February 1935 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

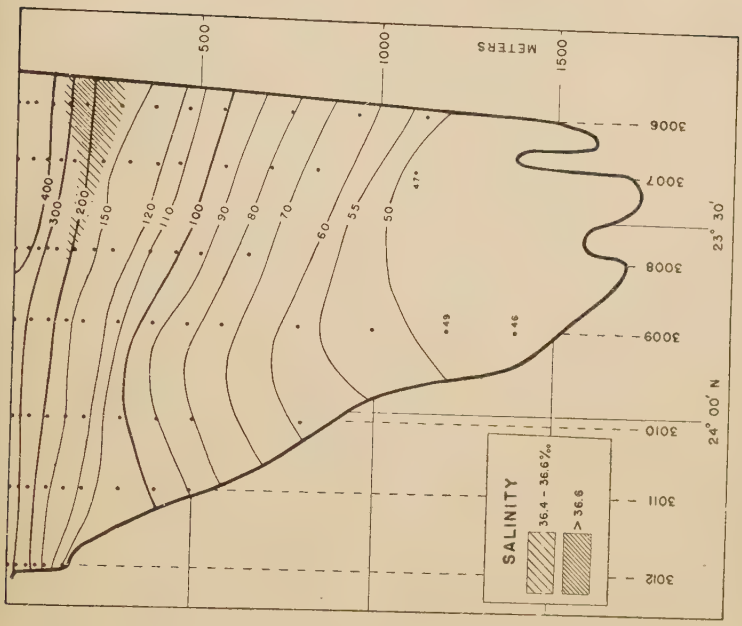

Figure 46. *Atlantis* Habana section on 24–25 March 1938 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

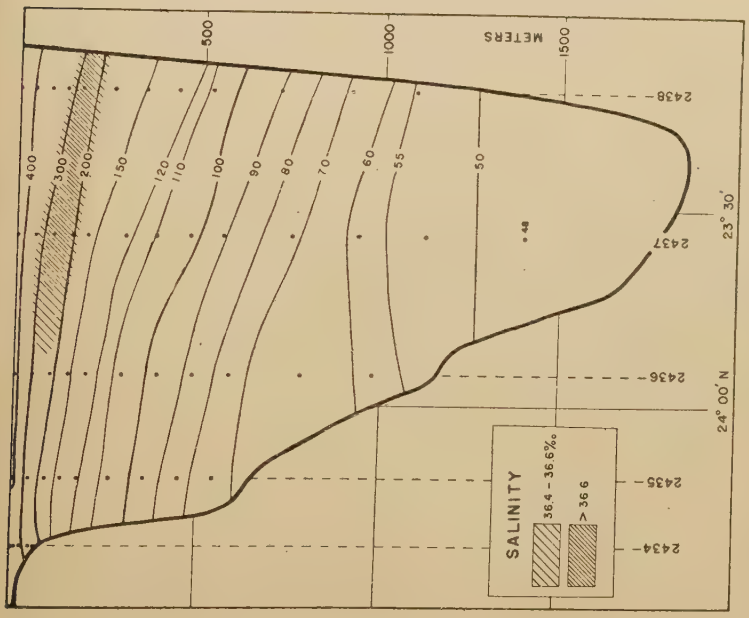

Figure 45. *Atlantis* Habana section on 12–13 April 1935 showing distribution of anomaly of specific volume in centiliters per ton. Vertical exaggeration about 100.

TABLE II—Anomaly of Geopotential, in Kilergs per Gram, Relative to 1200 db of the Sea Surface at the Northernmost Station of Each Section and at the Cuban Shore

Date	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24–25 III 38*	*Means*
Station No.	*2008*	*2347*	*2434*	*3012*	
Northern station	122.9	104.9	112.0	108.6	112.1
Cuban shore	170.4	172.4	172.5	170.6	171.5
Difference	47.5	67.5	60.5	62.0	59.4

TABLE III—Eastward Transports, in Million Cubic Meters per Second, Between Successive Isopleths of Anomaly of Specific Volume

δ *cl ton*$^{-1}$	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24–25 III 38*	*Means*
>400	0.00	0.00	2.34	4.97	1.83
300–400	7.67	9.35	6.37	3.81	6.80
200–300	3.78	6.24	4.80	4.61	4.86
150–200	5.76	4.83	4.38	3.94	4.73
120–150	3.38	3.74	4.00	3.59	3.68
110–120	1.40	1.39	1.28	1.31	1.34
100–110	1.54	1.63	2.38	1.11	1.66
90–100	1.09	1.42	1.67	0.98	1.29
80–90	0.70	0.86	1.05	0.82	0.86
70–80	0.41	0.75	0.63	0.60	0.60
60–70	0.21	0.12	0.10	0.44	0.22
55–60	0.07	−0.07	−0.01	−0.04	−0.01
50–55	0.02	0.02	0.00	−0.13	−0.02
Sums	26.0	30.3	29.0	26.0	27.8

(Jakhelln, 1936, p. 4), where z is elevation above the depth of 1200 meters and the integrations are performed for the walls. The agreement was good in each case.

The freedom allowed in extrapolating the mass distribution where there are no samples involves great uncertainty. For instance, the isopleths for the first section as shown in Figure 43 appear to give a reasonable interpretation on the basis of the observations, and give a total transport of $26.0 \cdot 10^6$ m^{3}sec^{-1}. However, another interpretation, appearing nearly as reasonable, gave $29.2 \cdot 10^6$ m^{3}sec^{-1}. The uncertainty in regard to the anomaly of dynamic height above 1200 db is relatively less. The two calculations for the first section give, in kilergs per gram:

	First calculation	*Second calculation*
Northern station	121.8	122.9
Cuban shore	171.8	170.4
Difference	50.0	47.5

Since the two calculations differ by much less than do the different sections as given in Table II, the values in that table are not in serious error due to incomplete knowledge of the mass distribution.

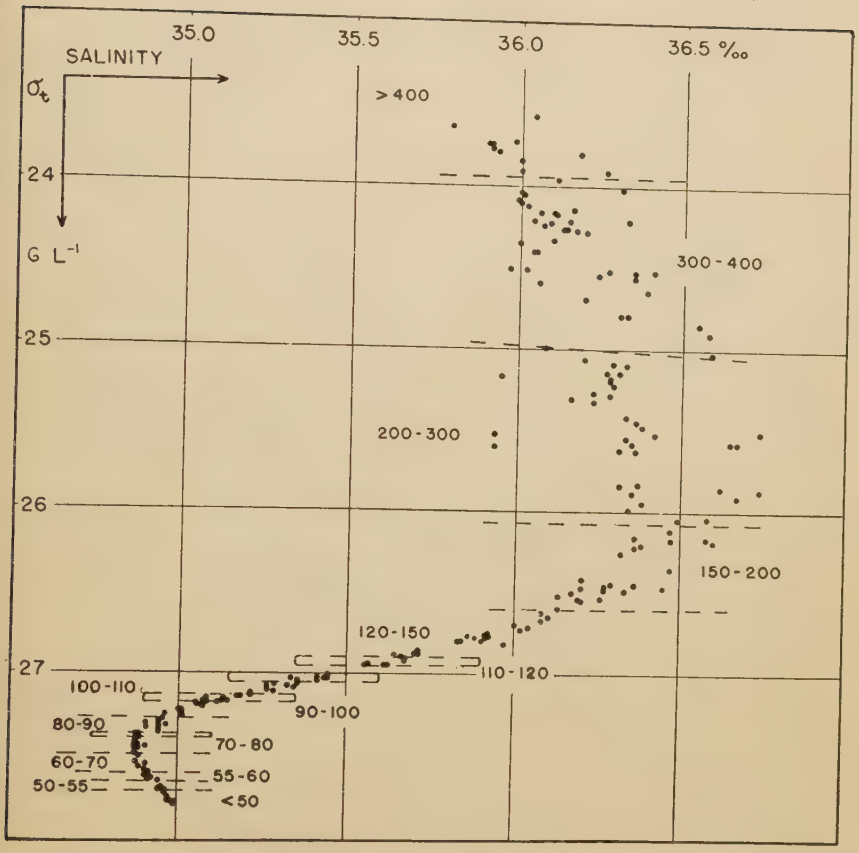

Figure 47. σ_t-Salinity correlations for all observations on the four *Atlantis* Habana sections, indicating also the anomaly of specific volume in centiliters per ton.

The base level of 1200 db was chosen rather than a deeper one because almost no observations below it were obtained.

Integration of curves of anomaly of specific volume versus pressure for the walls in order to obtain the anomaly of geopotential at points along the walls of course involves the questionable assumption that the horizontal pressure gradient vanishes at the walls.

When first suggested it was supposed that the acceleration potential would be computed for σ_t-surfaces, since these are usually best suited for isentropic analysis (Montgomery, 1937). The anomaly of specific volume is not entirely constant over a σ_t-surface (cf. Montgomery, 1938a, pp. 20–22), so $\Phi_a + \delta p$ is not strictly an acceleration

potential for such a surface and its use gives only approximate results. Accordingly, since surfaces of constant anomaly of specific volume have an exact acceleration potential, these have been used in the present study. This however introduces some inconvenience because specific volume anomaly is considerably less conservative than σ_t. This is illustrated by Figure 47, showing the overlapping with respect to σ_t of the layers of anomaly of specific volume.

In passing through the Straits the Florida Current turns cyclonically through nearly a right angle. Although there is no precise information on the direction of flow in all parts of the Straits, it is probable that the curvature starts before the Current reaches the Habana section. Since the cyclostrophic term in the equation of motion was neglected above in computing transport, the transports tabulated above are slightly too large. The radius of curvature of the axis of the Florida Current where it crosses the Habana section is about 500 km according to the U. S. Coast and Geodetic Survey Chart No. 1113. In the axis of the Current, where the speed is about 120 cm sec^{-1}, this would make the ratio of the cyclostrophic term to the Coriolis term 0.04. Taking the cyclostrophic term into account reduces the transport for the March 1934 section by 0.35 million cubic meters per second, or 1.3 per cent. This is so small, and the radius of curvature is so uncertain, that the correction term may suitably be neglected.

Each observation on all four sections is entered in Figure 47, which therefore serves also to show both the range of salinity and the average value for each layer of anomaly of specific volume. In the original drawing the points were differentiated according to the layers. This is indicated in the figure by broken lines. Where there is overlapping, two lines indicate the range of overlapping.

DISCUSSION

Pressure gradient at the bottom

The transport calculations were carried out on the assumption that there is no cross-stream horizontal pressure gradient at the bottom. It was at the Miami section of the Straits of Florida that Wüst (1924, p. 37) obtained his famous agreement between Pillsbury's current measurements and the density distribution deduced from *Blake* and *Bache* observations. His calculation of velocity distribution from density distribution was based on the absence of horizontal pressure gradient at the depth of the temperature minimum[4] in the

[4] Subsequent observations have not confirmed the existence of this temperature minimum. The temperature higher than 9° near the bottom as shown by Wüst therefore seems in error by several degrees.

central portion of the section, and at the bottom on the sides where the temperature minimum is lacking. Since the temperature minimum is shown less than 200 meters from the bottom, this gives evidence that the gradient is quite small at the bottom itself. In addition to this evidence and to the general fact that currents tend to be weak in deep water there are several considerations which indicate that the bottom gradient is small at the Habana section.

(1) *Bottom friction.* Any cross-stream pressure gradients which may arise at the bottom are automatically reduced by friction. This can be quite effective because the sources of currents and pressure gradients are to be found almost exclusively in the surface layers. For instance, in the deep central part of any section of the Straits of Florida a pressure gradient may arise due to some temporary cause. Bottom friction prevents complete development of a current to balance this pressure gradient, with the result that water flows from higher to lower pressure. Due to the confinement of the Straits a relatively small cross-stream transport of this sort is effective in reducing the gradient. It is unlikely that the cause of the gradient can be of both long duration and considerable magnitude, so bottom friction keeps the gradient small except for brief sporadic periods.

The "walls" of the Straits may be considered from the point of view of any layer bounded above and below by surfaces of constant potential density. This is largely an independent unit as far as frictional forces are concerned. In the central part of the layer the water is flowing through the section as part of the Florida Current, and the cross-stream pressure gradient is closely adjusted to this flow. Due to lateral friction (if not to other causes) the velocity gradually reduces to zero on approaching the wall at either side. Also in this manner adjustment of the pressure gradient takes place if possible, so that it tends to decrease toward zero at the walls.

(2) *Threshold.* The dense water of the lower layers found in the Habana section of the Straits cannot pass through the shallower sections further downstream. The threshold depth of the Straits is not well determined, but may be estimated very roughly as 800 meters. The threshold lies near Miami and the maximum σ_t observed in four sections from this vicinity are given in Table IV.

TABLE IV—Maximum Values of σ_t Observed on Four Miami Sections

Section	*Station*	*Depth (meters)*	*Temp ° C*	*Salinity °/oo*	σ_t $g\ l^{-1}$
Bache 19–20 III 14 (Bigelow, 1915, p. 58)	10203	800	6.16	34.85	27.43
Atlantis 17–23 IV 37 (Parr, 1937, Figure 3)	2855	600	6.00	34.90	27.50
Atlantis 27–28 III 38 (unpublished)	3016	579	7.45	34.91	27.305
Atlantis 22–23 V 39 (unpublished)	3506	729	6.06	34.88	27.475

From these values it may be concluded that very little water denser than $\sigma_t = 27.50$ g l^{-1} passes through the Straits. According to Figure 47 this coincides with an anomaly of specific volume of 70 cl ton^{-1} at the Habana section, so that the transport of the layers below this must be very small. The computed transports as given in Table III agree fairly well with this conclusion, showing that the assumption of no cross-stream pressure gradient at the bottom has led to only a slight inconsistency in this respect.

(3) *Current observations.* In Table V are given the surface currents measured from the *Blake* on the Habana section during parts

TABLE V—Pillsbury's Measurements of Current at 3½ Fathoms Below the Sea Surface on the Habana Section, February–May 1887

Station	*Miles south of Rebecca Shoal Light (24° 35′ N, 82° 35′ W)*	*Current strength (knots)*	*Current direction**	*East component cm sec⁻¹*	$\frac{d\Phi}{dx}$ *cm sec⁻²*
1	18	0.32†	——	16	0.0010
2	34½	0.96	SE x E ½E	43	0.0026
3	50½	2.20	E ¼ S	113	0.0066
3½	59	1.77	E ¾ S	90	0.0052
4	67	2.35	E x N	119	0.0069
4½	75½	1.13	NE x E ½E	51	0.0029
5	84	0.87	NE ½ N	29	0.0017

* From the small table on page 176 of Pillsbury's paper.
† East component.

of the months February–May 1887, taken from Pillsbury's (1887, Illustration No. 38, Fig. 1) graphical summary. The east component has been computed and in the last column is given the gradient of geopotential at the sea surface along the section,

$$\frac{d\Phi}{dx} = fv.$$

Here v is the east component of the current, and for each station the appropriate latitude has been used in computing the Coriolis parameter. The values of gradient in Table V have been integrated to give the geopotential of the sea surface along the section, represented by the continuous curve in Figure 48.

The same figure shows the geopotential of the sea surface as computed for each station of the four *Atlantis* sections. The form of the curve based on current measurement agrees well with an imaginary average of the four curves based on density distribution and on the assumption of no cross-stream horizontal pressure gradient at the bottom. In magnitude, the curve from current measurements is 52 kilergs g^{-1} higher at the Cuban shore than at the northern end,

whereas the differences between the Cuban shore and the northernmost stations of the *Atlantis* sections range between 47.5 and 67.5 kilergs g^{-1} (Table II).

This comparison cannot lead to definite conclusions because the two types of measurements were made at different times. The height difference from current measurements falls within the range of values from the four *Atlantis* sections, but is 7 kilergs g^{-1} less than the average of the latter. This indicates that the assumption of no cross-stream horizontal pressure gradient at the bottom is not consistently in large error, but that perhaps there is a tendency for

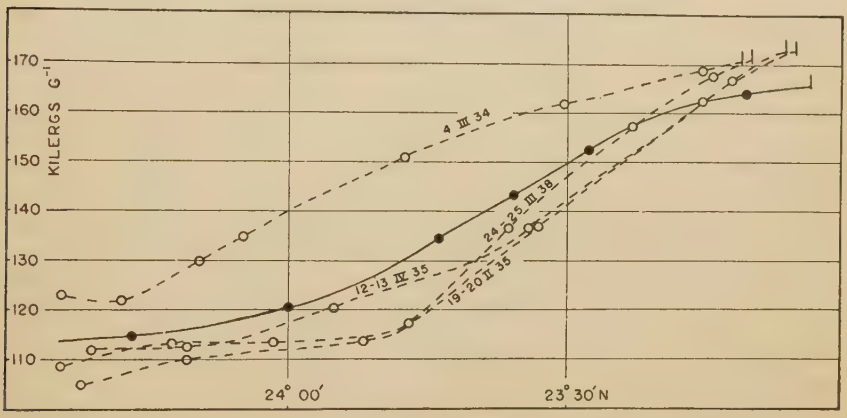

Figure 48. Profiles of sea surface at Habana section of the Straits of Florida. Solid line computed from *Blake* current measurements during February–May 1887. Broken lines computed from the mass distributions on the *Atlantis* sections, the ordinate being anomaly of geopotential above 1200 db. Vertical exaggeration about 10^6.

pressure at the bottom to decrease horizontally toward the right of the stream.

Tidal effects

Each of the four sections required about 16 hours to complete. The question arises as to what effect this lack of simultaneity may have on the observed mass distribution.

The tides and tidal currents in the Straits of Florida are of the mixed diurnal and semidiurnal type. The mean semidiurnal range of tide at Habana is 27 cm and the time of high water, 8^h 36^m after the moon's transit, is practically simultaneous with high water on the south side of the Florida Keys (Sombrero Key Light, American Shoal Light, Sand Key Light), where the mean range is 40 to 49 cm

(Coast and Geodetic Survey, 1940). It is reasonable to assume that the tide is similar all across the intervening strait. Since the range of tide is not identical on the two sides, however, there is necessarily a tidal variation in the cross-stream horizontal pressure gradient at the surface. The speed at the axis of the Florida Current also undergoes a tidal variation of amplitude about 14 cm sec^{-1}. To quote Pillsbury (1890, p. 608), "the maximum [flow] in the Straits of Florida is . . . 2 hours and 15 minutes after mean low water at the southern Atlantic ports of the United States." He further states that "off Cape Florida [Miami], there is but one prominent maximum each day, usually arriving 9 hours before the upper transit of the moon."

The *Atlantis* successively occupied five 24-hour anchor stations on a section crossing the Straits from Miami. The density distribution at the three western stations, 2854–2856, exhibit "a fairly distinct indication of a 12 lunar hours period in the upper 200 meters" (Parr, 1937, p. 20). The eastern stations, 2857 and 2858, "show no distinct periodicity with reference to lunar time." At the westernmost station, 2854 with depth of 375 meters, the geopotential of the sea surface above 300 db varied by 12 kilergs g^{-1}. At stations 2855–2858 the sea surface relative to 600 db varied by 30, 15, 6, 6 kilergs g^{-1} respectively (Parr, 1937, Figures 20, 21). Thus the variation is greatest where the slope of the isopycnals is greatest, and decreases toward the shore on each side.

Presumably similar conditions prevail at the Habana section. At the walls there may be little tidal or other short-period variation of density, so the calculated height of the sea surface at left and right shores and calculated total transport are not much affected. For these quantities, therefore, it is perhaps not significant that the density distribution was not measured simultaneously over the whole section. This conclusion is not substantiated by Parr's (1937, Table IV) values for every third lunar hour of the transport through the Miami section, which do vary. But this may easily be a fictitious variation, because (1) his sections for each third lunar hour are compositely formed from the anchor stations, (2) just as in the case of the Habana sections the observations do not completely determine the density distribution along the bottom, (3) he has not assumed the absence of horizontal pressure gradients at the bottom, which anyway is more doubtful at the constricted Miami section, and (4) his values do not include the considerable transport outside the two end stations.

If the tidal variations of density in the deep water and along the

walls are actually small, then the variations in horizontal pressure gradient at the surface must extend to the bottom. It is therefore probable that appreciable horizontal pressure gradients occur periodically at the bottom, but their average value may be expected to be small for reasons already stated. If so, they do not affect the calculation of total transport.

On the other hand there is a tidal lateral shift of the density distribution, producing large density variations at any point in the region of strong current. Hence the computed height of the sea surface at a station distant from the shore depends to large extent on the hour at which the station is occupied, and the computed transports of individual isosteric layers are presumably affected to a considerable degree.

Normal total transport through the Habana section of the Straits of Florida in March

By extrapolating his vertical velocity profiles downward from 130 fathoms, Pillsbury (1887, p. 179) obtained $103 \cdot 10^9$ tons per hour as the transport through the Habana section, which is equivalent[5] to about $28 \cdot 10^6$ m^3 sec^{-1}. A recalculation by Wüst (1924, p. 42) of the same measurements gave $24.15 \cdot 10^6$ m^3 sec^{-1}.

For comparison some estimated transports through other sections may be quoted. Wüst found for the Miami section $24.96 \cdot 10^6$ m^3 sec^{-1} based on the *Blake* current measurements and $25.55 \cdot 10^6$ m^3 sec^{-1} based on the density distribution deduced from *Blake* and *Bache* observations. For the same section Parr's (1937, p. 47) calculation from *Atlantis* anchor stations gives the transport as "somewhat more than" $30 \cdot 10^6$ m^3 sec^{-1}. From *Atlantis* stations made in 1933 and 1934 Parr computed 31.92 and 33.92 million cubic meters per second as the transport through the Yucatan Sea.

The values in Table III for the four *Atlantis* sections range from 26 to slightly over 30 million cubic meters per second. The fact that the two sections in March show lower values than the sections in February and April is probably not significant in regard to the annual variation of transport; in other words it should not be interpreted as indicating a minimum of transport in March. The four sections, all from nearly the same time of year, are probably sufficient to yield a significant estimate of the normal transport at this time. For no reason is it likely that these values differ consistently from normal by large amounts. In view of the scattering of the four values and of the possible error in the mass distribution as deduced

[5] Assuming the ton to be 2240 pounds.

TABLE VI—Departures from Normal in Centimeters of Daily Sea Level at Key West Reduced to Sea Level Pressure of 30.02 Inches (Normal Sea Level Is the Average for 1913–1939, Being Staff Reading of 4.95 Feet; Zero on Staff Is 13.06 Feet Below Bench Mark 29)

	III 34	*II 35*	*IV 35*	*III 38*
1	− 2.8	+ 8.1	− 1.6	− 3.6
2	− 2.3	+ 7.8	− 5.8	− 0.2
3	− 4.3	+ 6.5	− 4.0	− 3.6
4	− 7.5	+ 5.2	− 4.5	− 6.7
5	−12.1	+ 6.2	− 1.4	− 6.7
6	−10.7	+ 3.5	− 2.5	− 5.6
7	− 7.0	+ 2.7	− 1.9	− 7.0
8	− 7.5	+ 4.8	− 5.9	− 3.3
9	− 8.4	+ 4.1	− 3.0	− 2.6
10	− 9.2	− 2.5	− 3.0	− 5.9
11	− 9.7	− 1.3	− 1.8	− 6.7
12	− 8.1	− 3.7	+ 1.1	− 5.4
13	− 2.0	− 1.7	+ 3.1	− 5.2
14	− 5.1	− 5.6	+ 1.3	− 2.5
15	− 5.0	− 8.4	+ 3.8	− 5.0
16	− 1.8	− 9.6	+ 2.2	− 6.3
17	− 2.7	−13.7	+ 4.4	− 8.8
18	− 6.0	−17.8	+ 2.9	− 9.8
19	−12.3	−14.8	+ 4.2	− 6.9
20	−13.3	−11.9	− 0.7	− 5.4
21	−10.3	−10.5	− 3.7	− 4.7
22	− 7.2	− 4.5	− 2.3	− 1.8
23	− 7.1	− 4.6	− 1.7	− 1.8
24	− 5.3	− 8.2	+ 0.9	− 5.1
25	− 0.1	− 8.4	+ 0.4	− 5.8
26	+ 1.4	− 5.6	+ 1.5	− 3.6
27	+ 1.2	−10.7	+ 2.1	− 5.1
28	− 7.3	−11.8	+ 3.0	− 3.5
29	− 9.5		+ 0.4	+ 0.4
30	− 9.7		− 2.8	− 1.4
31	− 7.4			− 4.2
Means	− 6.4	− 3.8	− 0.5	− 4.6

from the observations it seems best to state the conclusion as follows: It is highly probable that the normal total transport through the Habana section of the Straits of Florida in March is a value lying between 26 and 30 million cubic meters per second.

The individual values obtained deviate from normal due to (1) actual departures of the transport from normal, (2) error in determining the mass distribution, (3) effect of tide on the mass distribution, and (4) presence throughout the tidal cycle of cross-stream horizontal pressure gradients at the bottom and of a deviation of the current from complete geostrophic flow.

Comparison with tidal station at Key West

Dietrich (1937, Abb. 15), Montgomery (1938b, pp. 166–169) and La Fond (1939, pp. 18–19) have found for specific localities a fair agreement between monthly or weekly sea level at tidal stations and fluctuations in sea level as computed from the vertical density distribution at nearby oceanographic stations. Good opportunity for such a comparison is offered by the northern station of each of the Habana sections, which lie near the primary tidal station at Key West.

The Director of the Coast and Geodetic Survey has kindly supplied the daily sums of the hourly heights of tide at this station for the months of the four sections. These have been converted to departures from the normal staff reading of 4.95 feet (Montgomery, 1941, Table I). To these departures were added the departures from normal of atmospheric pressure expressed in terms of a water barometer (departure in centimeters of water is 34.532 times the departure in inches of mercury), Table VI giving the resulting values. The pressure used was the average for hours 0800 and 2000, 75th meridian time, which were supplied by the Chief of the Weather Bureau. In regard to whether the tide is largely eliminated by this procedure, Marmer (1931, p. 51) says "it is sufficient to derive daily sea-level as the average of the 24 hourly heights of the tide of the civil day."

Table VII gives a comparison of computed sea level for the northern

TABLE VII—Comparative Values of Sea Level in Centimeters

Date		*4 III 34*	*20 II 35*	*12 IV 35*	*25 III 38*	*Range*
Northern station		+11.0	− 7.4	−0.1	−3.6	18.4
Key West	*day*	− 7.5	−11.9	+1.1	−5.8	13.0
	7 days	− 6.7	−11.1	+0.2	−3.8	11.3
	month	− 6.7	− 3.9	−0.9	−4.7	5.8

station, from Table II, with sea level at Key West for the appropriate day and for the seven days centered on the appropriate day, from Table VI. Mean sea level for the calendar month also is reproduced (Montgomery, 1941, Table I).

Monthly sea level at Key West shows no agreement with computed sea level at the northern station, while the daily and weekly values, which differ only slightly from each other, perhaps do show slight agreement with the northern station. The greatest disagreement is for the first section; compared with the averages of the other three it differs from the daily value at Key West by 14.4 cm. No extreme weather conditions prevailed when any of the sections were made.

Some of the discrepancy may be due to an actual difference in sea level between Key West and the northern station of the section. Evidence that sea level at Key West is perhaps not representative of conditions in the offshore water is to be found in the marked variations in the fall of sea level from Key West to Miami, individual monthly values ranging from — 3.1 cm to 11.9 cm (Montgomery, 1941).

On the other hand if there is little difference in sea level between Key West and the northern station, and if the density distributions for the four sections were correctly extrapolated to the northern wall and their tidal variation and horizontal pressure gradients at the wall are negligible, there must be a non-tidal variation in elevation of the 1200-db surface. Although such pressure variations in deep water have not heretofore been noted, it is conceivable that they should exist, especially in the partially enclosed Central American seas, where the circulation and density distribution is controlled by the variable trade wind system.

Fluctuations in transport of the Florida Current

The computed transport for each of the four sections was given in Table III. Due to the uncertainties already discussed the significance of the fluctuations is questionable, although their magnitude is quite as one might expect.

If the computed fluctuations are essentially real, there is value in comparing them with the computed sea level difference across the Straits, as in Table VIII. The agreement between sea level differ-

TABLE VIII—Transport of the Florida Current in Million Cubic Meters per Second in Relation to the Computed Sea Level Difference Across the Straits (from Tables 2 and 3)

Date	*4 III 34*	*19–20 II 35*	*12–13 IV 35*	*24–25 III 38*
Sea level difference, kilergs g⁻¹	47.5	67.5	60.5	62.0
Total transport	26.0	30.3	29.0	26.0
Transport above δ = 200 cl ton⁻¹	11.4	15.6	13.5	13.4
Transport above δ = 300 cl ton⁻¹	7.7	9.4	8.7	8.8

ence and total transport is poor. The sea level difference is however seen to be closely correlated with the transport of water having

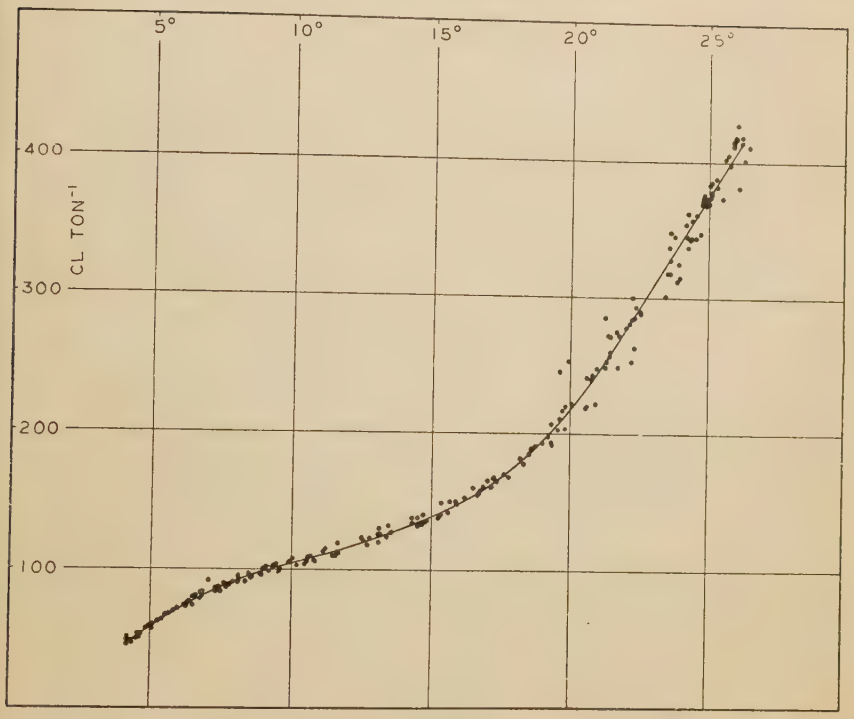

Figure 49. Correlation of temperature with anomaly of specific volume for all observations on the four *Atlantis* Habana sections.

anomaly of specific volume greater than 300 cl ton^{-1} (warmer than about 23° C) or greater than 200 cl ton^{-1} (warmer than about 19.2° C, see Figure 49). This suggests that fluctuations in the transport of warm water through the Straits might be measured with a pair of tidal stations placed on opposite sides and in good exposures. Perhaps the pair of stations now operating further downstream, at Miami and Cat Cay, will prove to serve this purpose at that section.

The deep counter current on the left of the Florida Current

On all the four sections except the first the deeper isopleths of anomaly of specific volume dip downward toward the northern wall (Figures 43–46), indicating a counter current. The calculations showed negative velocities extending up to anomaly of specific volume 70 cl ton^{-1} or 600 meters on the second section, up to 80 cl ton^{-1} or 500 meters on the third section, and up to 200 cl ton^{-1} or 80 meters on the fourth section.

In regard to this section Pillsbury (1890, p. 551) states: "The current does not fill the banks . . . , but has on its northern edge a neutral zone of varying width, in which, at times, there is an eddy current setting to the westward. At Station 1, which is within this zone and about 3 miles from the 100-fathom curve, tidal currents were always found except on one occasion, . . ." According to the data (Pillsbury, 1887, Illustrations Nos. 35 and 36) this station was occupied for about 24 hours on each of three occasions. On the first occasion the current was predominantly about a half knot west at 65 and 130 fathoms and irregular above that. On the other two occasions the current at the deeper levels was irregular, and at higher levels it was predominantly west in one case and east in the other. Pillsbury's measurements do not extend down to the depths where the *Atlantis* sections indicate a predominant counter current.

The counter current appears therefore to be a normal feature of the Habana section of the Straits in late winter. It is most persistent at depths immediately below the threshold of the Straits; it often extends much higher, but there is apparently no evidence that it ever reaches completely to the sea surface. Thus there is reason to believe that the counter current does not extend far eastward, and that it is a characteristic of the deep embayment upstream from the threshold, where also the Florida Current is closest to the right bank.

SUMMARY

A total of four hydrographic sections crossing the Straits of Florida near Habana were executed from the *Atlantis* during the winter months of 1934, 1935 and 1938. From the observed mass distribution the water transport in various layers (defined by surfaces of constant anomaly of specific volume) has been computed by use of the acceleration potential (Table III). The computed total transport varies for the four sections from 26.0 to 30.3 million cubic meters per second, and the conclusion was drawn that probably the normal transport in March is a value lying between these extremes. The assumptions and various sources of error involved in the calculation have been discussed.

The four values of sea level computed for the northern end of the sections show no appreciable correlation with sea level observed at the nearby tidal station at Key West.

The computed difference of sea level across the Straits shows little correlation with the computed total transport, but good correlation with the computed transport of the lighter surface water.

A counter current in the deep water on the left of the Florida Current appears to be a characteristic of this part of the Straits.

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OBSERVATIONS ON TRANSPARENCY IN THE SOUTHWESTERN SECTION OF THE NORTH ATLANTIC OCEAN

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The present measurements were undertaken to extend our knowledge of the transparency of ocean waters to areas to the south of the Bermuda region and to the east of the Caribbean region beyond the limits of earlier investigations (Oster and Clarke, 1935; Clarke, 1938 and 1939). The measurements were made from the research vessel "Atlantis"* between January 19, 1941 and March 7, 1941 on Cruise No. 111 which extended from Bermuda to the northeast coast of South America and back to New York. The positions of all stations where observations were made are indicated in Figure 50.

It was desired not only to determine what variations existed in the average transparency of the different areas of the sea traversed, but also to ascertain whether any changes in the rate of the penetration of daylight occurred with depth down to levels of 50 meters or more. Another object of the investigation was to learn how closely simple Secchi Disc determinations agreed with the transparency values obtained from the more elaborate Photronic cell photometer. Since Secchi disc measurements require only a few minutes, they might be used to supplement the more time-consuming photometer measurements if good agreement were found.

PROCEDURE

At every station a standard series of measurements was made by comparing the readings of two photometers, one of which was mounted on deck and the other lowered into the sea. Each photometer contained a Weston Photronic cell, the spectral sensitivity of which ex-

* Contribution No. 306.

* The measurements at sea were carried out by Mr. A. H. Woodcock and the calculations and graphs were prepared by Mr. D. F. Bumpus, of the Woods Hole Oceanographic Institution.

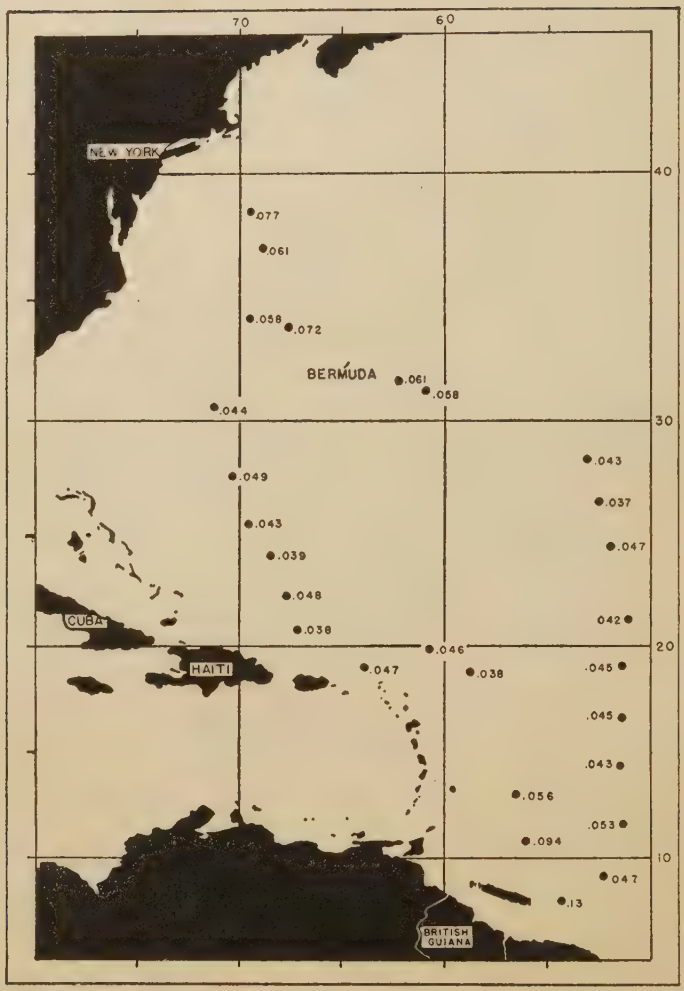

Figure 50. Location of stations where observations were made. Figures give the average value of the extinction coefficient, k, (Column 7, Table I) for range from 2 meters to greatest depth at which observation could be made (Column 6, Table I).

hibits a maximum at 5800A and drops off to 10% of the maximum at 7080A and at 3420A. A diffusing disc of opal glass was placed over each photometer but no color filter was used. In general, the same procedure was followed as in the earlier investigations of the author. All measurements were made between 10:45 a. m. and 2:45 p. m. E.S.T. At the same time that these precise determinations were

being carried out with the Photronic cells, a rough visual measure of transparency was made by lowering a Secchi disc (white disc 20 cm. in diameter) into the water and noting the depth at which it disappeared.

The 27 series of measurements with the Photronic cell photometers are summarized in Table I. In each case the range in depth over which the series extended is indicated (Column 6). The first determination was made as near the surface as circumstances permitted (usually at 2 meters) and succeeding readings were taken ordinarily at 6, 10, 15, 20, 25 and 30 meters and thereafter at every ten meters to the greatest depth at which the instrument would respond. The value of the extinction coefficient,* k, for the entire range of depth indicated for each series is given in Column 7. For the sake of uniformity, the value of the extinction coefficient down to 50 meters only has also been worked out and is presented in Column 8. Although certain differences exist in some cases between these values and the extinction coefficients for the entire range in depth, the variance is slight and the same general picture of the regional distribution of transparency is obtained from either set of data.

TRANSPARENCY CURVES

A large number of the transparency observations on this cruise were made under very unfavorable weather conditions and consequently considerable irregularity appeared among the individual measurements of each series. Nevertheless the trend of the measurements is consistent in most cases, as may be observed from the sample set of curves presented in Fig. 51. From the straightness of these semi-logarithmic plots and from the curves for all the other series of measurements, it is learned that there was no important change in transparency with depth at any station. In other words, the water tended to be optically homogeneous in each case down to the depth to which the series extended.

Of the individual series of measurements Series 534, made February 21, 1941 at Station 4121 (about 750 miles Southeast of Bermuda), is of particular interest because of the extremely great transparency it represents. The average value of the extinction coefficient over the range 2 to 133 meters was $k = .037$ and individual segments of the curve give an even lower value. The Secchi Disc depth was 41 meters at this station. The lowest value obtained previously with a photometer of similar, though not identical, spectral sensitivity was $k = .042$

* Extinction coefficient $= k$ in the equation $I/I_0 = e^{-kL}$ where the light is reduced from I_0 to I by a stratum L meters thick.

TABLE I—Summary of Transparency Measurements with Photronic Photometers and Comparison with Secchi Disc Determinations

1	2	3	4	5	6	7	8	9	10
Series Number	*Atlantis Station*	*Position* *Latitude*	*Longitude*	*Date 1941*	*Depth Range for Series*	*Extinction coefficient, k*	*Ext. Coeff. for range 2–50 m.*	*Max. depth of visibility of Secchi Disc*	*% surface light at Secchi Disc depth*
530	4108	33° 51′ N	67° 37′ W	Jan. 19	6–85 m.	.072	.068	19 m.	26%
1	4111	31° 40′	62° 16′	24	1–127	.061	.066	(40)	(4.3)
2	4112	31′ 12°	60° 55′	25	2–65	.058	.059	23	15
3	4119	28° 17′	53° 09′	28	2–102	.043	.049	39	17
4	4121	26° 26′	52° 34′	29	2–133	.037	.038	41	11
5	4123	24° 31′	51° 57′	30	2–85	.047	.046	32	15
6	4127	21° 09′	51° 03′	Feb. 1	2–126	.042	.042	37	15
7	4129	19° 00′	51° 18′	2	2–101	.045	.044	39	13
8	4131	16° 39′	51° 26′	3	2–77	.045	.044	35	23
9	4133	14° 21′	51° 27′	4	2–66	.043	.043	35	19
540	4135	11° 34′	51° 20′	5	2–77	.053	.050	38	15
1	4137	9° 02′	52° 17′	6	2–85	.047	.055	40	9.3
2	4139	7° 53′	54° 19′	7	2–55	.13	.13	13	18
3	4141	10° 46′	56° 01′	8	2–47	.094	.092	(36)	(3.6)
4	4143	13° 01′	56° 33′	9	2–50	.056	.059	21	18
5	4147	18° 49′	58° 47′	11	2–52	.038	.040	43	13
6	4149	19° 51′	60° 47′	12	2–46	.046	.048	34	13
7	4151	18° 59′	63° 54′	13	2–74	.047	.042	33	15
8	4155	20° 42′	67° 11′	21	2–109	.038	.036	47	12
9	4157	22° 16′	67° 45′	22	2–69	.048	.050	33	15
550	4159	24° 06′	68° 25′	23	2–99	.039	.040	37	20
1	4161	25° 29′	69° 34′	24	2–80	.043	.035	36	19
2	4163	27° 35′	70° 19′	25	2–85	.049	.048	33	15
3	4167	30° 36′	71° 14′	27	2–67	.044	.045	30	17
4	4170	34° 17′	69° 26′	Mar. 3	2–83	.058	.058	31	11
5	4172	37° 03′	68° 52′	6	2–95	.061	.072	27	8.0
6	4174	38° 30′	69° 35′	7	2–86	.077	.079	21	9.6

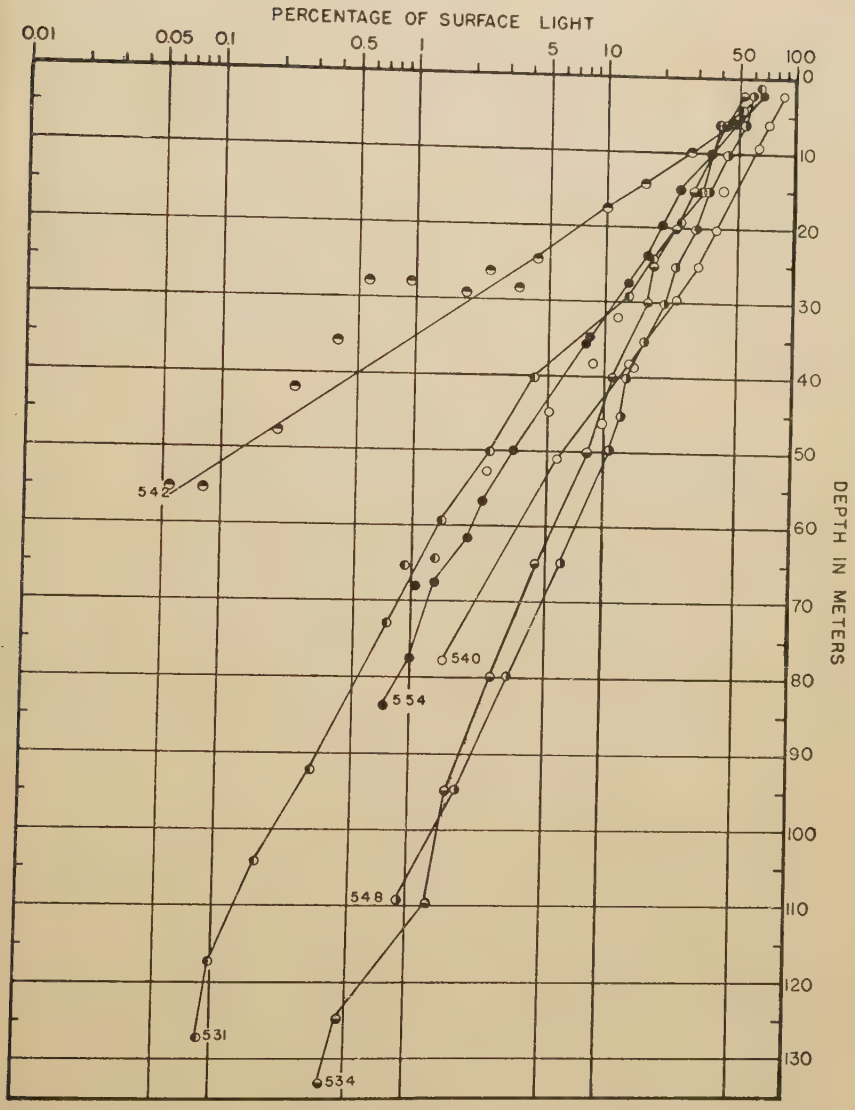

Figure 51. Sample set of curves showing percentage of light incident on the surface which reaches the depths indicated (semi-logarithmic plot). Series number appears at end of each curve. For complete data see Table I.

for the range 2 to 185 meters ($k = .038$ for the range 95–185 meters) in the Cayman Sea, west of Jamaica (Clarke, 1938, p. 90). In the present investigation average values for the extinction coefficient which were almost as low as in Series 534 were obtained at three other stations (See Fig. 50). The greatest value for the Secchi Disc determination was at Station 4155 (about 130 miles northeast of Puerto Rico) where the disc was seen at 47 meters. On this occasion, calm weather allowed the disc to sink without departing appreciably from the vertical and made possible an unusually precise determination with the Photronic photometer (Series 548, $k = .036$ for range 2–50 meters). The greatest previous depth for the visibility of the Secchi Disc of which I am aware is 40 meters for Crater Lake, Oregon (Hasler, 1938).

REGIONAL DISTRIBUTION OF TRANSPARENCY

The observations made across the North Equatorial Current from Latitude 29° N. to Latitude 14° N. between Longitude 51° W. and 53° W. yielded low values for the average extinction coefficient, all of which fell between $k = .037$ and .047. Similarly, low values, ranging from .038 to .049, were obtained for measurements made from a point about 200 miles off Antigua northwestward in the water of the Antilles Current to a point about 360 miles southwest of Bermuda. We may therefore conclude that this region lying south of Bermuda and north and west of the Antilles is one of very high and relatively uniform transparency. In fact, the values obtained represent the clearest ocean water known.

Farther to the south the transparency is somewhat reduced and at the southernmost station in the Guiana Current about 100 miles off the coast of Guiana the extinction coefficient rose to $k = .13$. At this point and at the next station to the northwest the clearness of the water was distinctly less than at the stations farther offshore.

At the stations immediately southeast of Bermuda and at those northwest of the Island and toward New York, water of intermediate transparency was encountered. The values of the extinction coefficient ranged from $k = .058$ to .077 in this region. These values and those for the larger area to the south agree well with the few measurements carried out during earlier investigations near these regions.

COMPARISON WITH SECCHI DISC MEASUREMENTS

The Secchi Disc measurements (Table I, Column 9) may be compared graphically with the values for the extinction coefficients for

the depth range of 2 to 50 meters as determined by the Photronic cell photometers in Fig. 52. It is seen that the majority of measurements fall between $k = .040$ and .050 and that these are accompanied by Secchi Disc values lying between 30 meters and 40 meters. Higher extinction coefficients are correlated with lower Secchi Disc values. However, the scatter in the correlation is considerable and it is de-

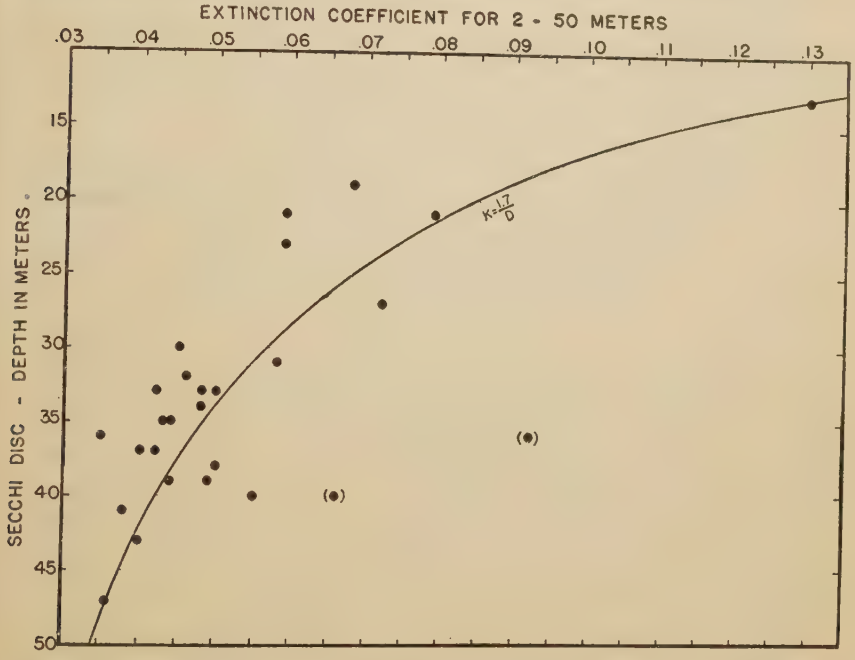

Figure 52. Correlation chart of the Secchi disc determinations and the extinction coefficients from the Photronic photometer measurements for range 2 to 50 meters. Curve of the equation $k = 1.7/D$ has been superimposed.

sirable to ascertain whether the lack of agreement is due primarily to the relative crudity of the Secchi Disc measurement or to some other cause.

Measurements with the Secchi Disc can ordinarily be repeated with a variation of less than one meter but during the present cruise unfavorable weather conditions were encountered at a large number of the stations. The large size of the waves and the irregularity of the light reflected from the surface interfered seriously with the determinations. (The use of a tube passing beneath the surface through which the investigator may observe the disc is indicated for

future work.) Furthermore, the drift of the ship was such that in many cases the cord supporting the disc acquired an angle of 30° or more to the vertical. Although the vertical depth of the disc could be calculated (if the cord be assumed to have been straight), as is always done in the case of the Photronic photometer, this procedure would not give a correct value for the limit of visibility since the path of the light *from the disc to the observer's eye* follows the angle of the supporting cord. In view of this complication it did not seem worth while to attempt a correction for the angle of stray and the values given are the total length of cord from the surface to the disc.

Errors of measurement may therefore account for a part, or all, of the irregularities in the correlation of the Secchi Disc measurements and the extinction coefficients. Another possible explanation, which must be borne in mind, is the fact that in two cases in which the actual amount of light reaching a certain depth is identical (as measured by the Photronic cell photometer), the relative parts played by the processes of *scattering* and true *absorption* may be very different. In the situation in which scattering is greater, the light from the Secchi Disc would be more highly diffused and hence the disc would be less easily recognized from the surface. Such a condition has been reported for lakes (Sauberer, 1939). In the case of the ocean, this possibility, that there may be important differences in the relative roles of scattering and absorption from place to place in addition to the already recognized variation in the "total" rate of light extinction should be carefully tested in as many situations as possible.

The relation between the value of k, the extinction coefficient, as determined by a photometer and D, the depth for the limit of visibility of the Secchi Disc was found by Poole and Atkins (1929) on the basis of their measurements off Plymouth, England, in water of lower transparency ($k = .088$ to $.203$) to be described roughly by the equation $k = 1.7/D$. A curve expressing this relationship has been drawn on the correlation graph (Fig. 52). It is seen that this curve agrees remarkably well with the average position of the points. If the two observations represented by points within parentheses are rejected as probably in error because of their wide divergence, then the remaining points fall satisfactorily within a band of moderate width, the axis of which is described by the above equation.

The magnitude of the illumination at the depth at which the Secchi Disc is just visible is of interest and has been determined from the curves of light penetration at each station. This may be given as

percentage of light incident at the surface as experience has shown (cf. Poole and Atkins, 1929) that differences in the value of daylight may be neglected if measurements are made near the middle of the day (as was the case in this investigation). The percentage of the light at the surface which existed at the depth obtained for the Secchi Disc appears in Column 10 of Table I. It is observed that the illumination varies from 8.0% to 26% (omitting the two questionable observations) with an average of 15.2%. These values agree very closely with those of Poole and Atkins (1929) who reported a variation for his set of 14 series of measurements from 9.6% to 22.6% with an average of 15.8%. This range in the percentage illumination and the width of the band in the correlation graph (Fig. 3) are a measure of the extent to which the photometric and the visual methods of transparency measurement agree. Further work is called for to determine how much of the discrepancy is due to error of measurement, and how much to differences in the optical properties of the water.

SUMMARY

1. Twenty-seven series of light penetration measurements were made with Photronic cell photometers to depths as great as 133 meters in the southwestern section of the North Atlantic Ocean.

2. The water exhibited no important change in transparency with depth. A minimum average value for the extinction coefficient of $k = 0.037$ and a maximum depth for the Secchi Disc of $D = 47$ meters were observed.

3. The region south of Bermuda and north and west of the Antilles was found to contain the clearest ocean water known and to be relatively homogeneous in respect to transparency. Off the coast of Guiana a sharp drop in transparency was encountered. To the southeast and to the northwest of Bermuda, the water is very clear but less so than farther to the south.

4. A comparison of the Photronic photometer measurements with the Secchi disc determinations shows in general good agreement with the relation, $k = 1.7/D$, reported by Poole and Atkins. At the depth of disappearance of the disc the illumination averaged 15% of the light incident at the surface. Individual variations suggest the possibility that important changes in the relative effects of scattering and absorption may occur in ocean waters.

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RELATION OF POPULATION SIZE TO MARINE GROWTH AND TIME OF SPAWNING MIGRATION IN THE PINK SALMON (*Oncorhynchus gorbuscha*) OF SOUTHEASTERN ALASKA

By

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INTRODUCTION

In studying the relation of an animal population to its environment it must always be remembered that the population forms part of its own environment. This is due mainly to the influence its size has upon the other elements, both physico-chemical and biotic, of the environment. Allee (1931) in his discussion of the harmful effects of crowding upon growth separates the growth retarding factors into two groups namely, the vague and the definite. Those in the first group consists of such factors as the X-substance of Semper (1874–1881), the autotoxins of the bacteriologists, Henrici (1928), and the growth inhibiting substances of the tissue culturists, Heaton (1926). He refers to this group of factors as being at present unproved but of value as working hypotheses. Those in the second group consist of the more tangible factors such as insufficient aeration, accumulation of excretory products, reduction in available food and overstimulation of the individuals due to increased contacts. Either one or a number of these factors have been shown to be effective in the growth of tadpoles as studied by Yung (1885), Bilski (1921), and Goetsch (1924), in the growth of snails by Willem (1896), Colton (1908), and Crabb (1929) and in fish by Church (1927), Willer and Schnigenberg (1927) and Shaw (1929).

It is to this second group of growth retarding factors that the authors turn for the explanation of the influence of population size on the growth and time of spawning migration of the pink salmon. This study was made in part through the analysis of commercial fishery data and in part through direct observations of the fish populations under natural conditions. Field studies of this kind provide

[1] The United States Bureau of Fisheries was combined with the United States Bureau of Biological Survey on July 1, 1940 to form the Fish and Wildlife Service.

opportunity for the application of ecological principles and the theoretical interpretation of biological relationships in the ocean.

LIFE HISTORY OF PINK SALMON

The pink salmon (*Oncorhynchus gorbuscha*) like the other species of Pacific salmon are anadromous. The eggs are spawned in the gravel beds of the streams in the fall of each year and hatch the following spring. The fry after absorption of the yolk sac emerge from the gravel, and migrate directly to the ocean where they feed until the summer of their second year of life. During their 16 to 18 month sojourn in the ocean they make over 95 per cent of their growth. After attaining maturity in the ocean they return to the streams to spawn and die. The adults begin to migrate into the streams in July and continue through August and part of September. By the middle of September most of the salmon have entered the streams and spawning is well under way.

This two-year cycle of the pink salmon has been found by Davidson (1934) and Pritchard (1932 and 1939) to be very consistent. In fact, all evidence thus far available indicates that this species has an invariable two-year life span and is distinctly different from the other species of Pacific salmon in this respect.

PINK SALMON AGGREGATIONS

Although detailed information is not available concerning the habits of the pink salmon while in the ocean, it is known that they migrate seaward in schools of immense size and return in similar aggregations. The fry migrate from the streams almost exclusively at night. Upon reaching the bays at the mouths of the streams they collect into schools of varying size and remain near the shores for a time before migrating into the open channels and seaward. At times the schools of fry from many bays may congregate into vast swarms as they migrate to the open ocean. Dense bodies of these fry have been observed that cover surface areas ranging from 15 to 25 yards in width and from 75 to 100 yards in length. Since the young salmon at this age are not more than 1½ inches long such aggregations are composed of millions of individuals. These symporia or societies are formed during their migration through the larger channels where they are subjected to the inroads of many predators.

At maturity the adult pink salmon appear near the surface in the ocean and migrate shoreward to the streams. Dense schools of these fish have been observed as far as 15 miles offshore covering a surface area from 1500 to 2000 square yards in extent. Similar aggrega-

tions have also occasionally been observed in the larger inside channels. As a rule, however, the adult salmon migrate in schools of a few hundred to ten thousand individuals in the inside channels and inlets.

FLUCTUATIONS IN SIZE OF PINK SALMON POPULATIONS

Any characteristic of an animal population related to its abundance must be studied from a long time standpoint in order to gain a true perspective of the relationship. Since adequate statistics of the pink salmon fishery in southeastern Alaska during the early years of the industry are not generally available it was necessary to select a representative area within the region wherein such statistics could be secured. The Clarence Strait area which includes the waters of Clarence Strait, Behm Canal, and Revillagigedo Channel was selected for this purpose. These waters form some of the oldest fishing grounds in southeastern Alaska and have consistently produced a large part of the total pink salmon packs of the region each year. The statistics of the fishery in this area cover a period from 1895 to 1940. The statistics during the first half of this period were secured from the records of two old-line canneries operating in the area and those for the latter half of the period from the records of a number of the canneries operating in the area as well as from the records of the fish traps in the area.

Although commercial fishing for pink salmon in southeastern Alaska is carried on by means of traps and purse seine boats the traps account for 70 to 80 per cent of the fish caught. The traps are stationary units of gear and are operated along the shores of the larger inside channels where they intercept the salmon on their migration to the streams. If a method were to be devised for sampling the populations of salmon for the purpose of studying periodic changes in their characteristics and habits no better one could be found than that incorporated in the present trap fishery. The average yearly and daily catch records of the traps provide extensive and comparable data on the yearly abundance and seasonal time of the spawning migration of the salmon.

If the number of traps operating in the area had remained constant from year to year then their average yearly catches could have been used directly as a relative index of the yearly abundance of the salmon. Since this was not the case, however, it was necessary to eliminate the influence of competition between the traps created by the yearly changes in their numbers. Owing to the non-linear relationship between average yearly catch per trap and number of

traps operated, and likewise the non-linear regression of both on time (period of years operated) it was impossible to use a correlation analysis to eliminate the influence of competition between the traps by making the number of traps constant and then determining the regression of average yearly catch on time. Hence an empiracle method was employed wherein a regression curve representing the yearly catches of traps of varying numbers from populations of comparative uniformity in size was used as a basis to calculate the relative abundance of each season's populations from the average yearly catches observed. This relative index of abundance was expressed in percentage of the base year 1921 for it was in that year that the populations in the area reached their lowest level of abundance. See Figure 53.

The upper graph in Figure 53 shows the trend in the relative size of the pink salmon populations in the Clarence Strait area from 1895 to 1940. That part of the graph from 1913 to 1940 describes the relative abundance of the salmon as determined from the average yearly catches of the traps operated in the area during the period. Since trap catch records were not available in the area prior to 1913 the data upon which that part of the trend from 1895 to 1913 was determined were secured from the yearly catches of the canneries operating in the area and estimates of the abundance of the salmon cited in the Commissioner of Fisheries reports for these years.

From 1895 to 1911 the pink salmon fluctuated at a relatively high level of abundance with the exception of 1905, which was a comparatively poor year. In view of the statements in the Commissioner of Fisheries reports for these years, it is estimated that the size of the pink salmon populations during that period, although not as great as the peak years of 1934 and 1936, were considerably above the average for the period 1910 to 1940. From 1911 through 1921 there was a steady decline in the abundance of the salmon with the greatest rate of decline occurring just prior to 1921. This decline in abundance of the salmon following 1911, was due primarily to the unlimited exploitation of the resources by the commercial fishery. From 1921 to 1936 there was a decided upward trend in the size of the pink salmon populations and although those of 1937, 1938, 1939 and 1940 fell below 1934 and 1936 they were still above average for this period.

This rehabilitation of the pink salmon populations following 1921 was due to the introduction and enforcement of an adequate conservation policy by the Bureau of Fisheries. The abundance of the pink salmon in southeastern Alaska was not only restored but in-

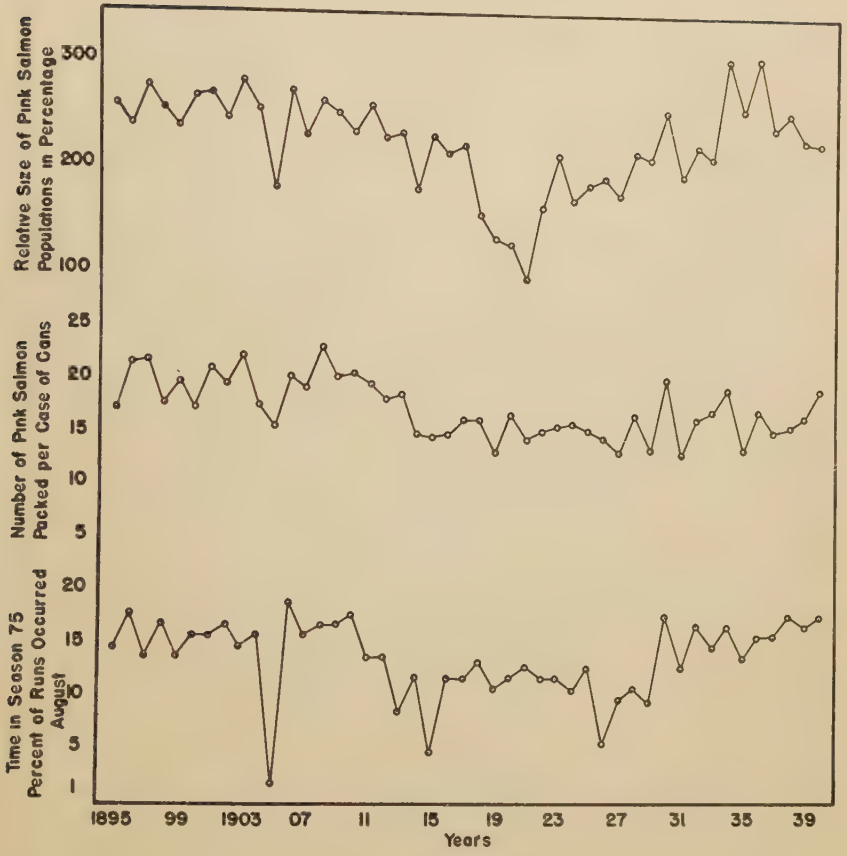


Figure 53. Cyclic changes in the characteristics of the pink salmon populations in the Clarence Strait area of southeastern Alaska from 1895 to 1940. (1) Relative size of pink salmon populations, (2) growth of individual fish as indicated by the yearly number of fish packed per case of salmon and (3) the seasonal time of their spawning migration.

creased under the controlled management of the Bureau of Fisheries. This is a good example of the manner in which our natural resources may be maintained through the application of wise husbandry in their management.

FLUCTUATIONS IN GROWTH OF PINK SALMON

Since the pink salmon have an invariable two year life cycle the size they attain at maturity may be used as a measure of their rate of growth during their sojourn in the ocean. In other words, in

years when the adult salmon are small in size it may be assumed that their growth in the ocean was slow and in years when the salmon are large it may be assumed that their rate of growth in the ocean was rapid.[2] The records of the canneries provide a means of determining the relative size of the individual fish each year, in that they keep account of the number of fish packed per standard case of canned salmon.

The middle graph in Figure 53 gives the number of pink salmon packed per case of salmon each year in the Clarence Strait area from 1895 to 1940. From 1895 to 1911 the salmon averaged 20 to the case. Following 1911 they tended to become larger, taking only 13 per case in 1919. From 1914 to 1929 they were consistently larger than during the early years of the fishery and averaged 15 to the case. Following 1929 they became erratic in size from year to year but were somewhat smaller averaging 17 to the case. Reference to the size of the pink salmon in the Commissioner's reports for the early years of the fishery show that the fish were small during this period with the exception of 1904 and 1905 when unusually large fish occurred in the runs.

In a comparison of the upper and middle graphs in Figure 53 it will be found that during the early years of the fishery when the salmon were relatively abundant the fish were relatively small in size. From 1911 to 1921, during which period the abundance of the salmon progressively declined, the fish tended to increase in size, i. e. it required fewer fish to fill a standard case of cans. Following 1921, when the Bureau of Fisheries began to introduce more adequate measures for the conservation of the salmon, their abundance began to increase and in 1930 when their abundance reached the level of that in the early years of the fishery the individuals composing the populations tended to become smaller in size, i. e. it required larger numbers to fill a case of cans. In other words, there appears to be an inverse relationship between the size of the pink salmon populations and the size of the individuals that compose them. That is, larger populations tend to consist of small fish with slow growth and smaller populations tend to consist of large fish with rapid growth. A similar relationship between density of population and rate of growth has been observed by Raitt (1939) in the haddock populations of the North Sea, and by Hile (1936) in the cisco populations of Wisconsin lakes.

[2] Owing to the marked homing tendency in the pink salmon (Davidson, 1934 and Pritchard, 1939) the stream populations are in general highly inbred. Therefore, it is very improbable that the yearly differences in the size of the salmon could be due to chance variations in the genetic composition of the fish.

FLUCTUATIONS IN THE SEASONAL TIME OF SPAWNING MIGRATION OF PINK SALMON

As previously pointed out the adult salmon begin to migrate into the streams in July and continue through August and part of September. However, the numbers that migrate into the streams during each of these months is not the same from year to year. There have been years when the salmon migrated to the streams early in the season and the majority of the fish either entered the streams or collected in the bays at the mouths of the streams during July and early August. On the other hand, there have been years when the salmon migrated to the streams late in the season and the majority of the fish did not appear in the streams or bays until late in August.

The seasonal time of appearance of the runs in the Clarence Strait area prior to 1913 were determined from the date in the season upon which 75 per cent of the pink salmon catches had been delivered to two old-line canneries operating in the area. The time of appearance of the runs in the years from 1913 to 1940 were determined from the dates in the seasons upon which 75 per cent of the pink salmon trap catches in the area were made. Since commercial fishing in the area following 1924 has not been permitted in most years after August 23, all of the data were truncated on this date in order to make them comparable for analysis of time of run.

The lower graph in Figure 53 shows the trend in the time of appearance of the pink salmon runs from 1895 to 1940 as determined by the methods just described. From 1895 to 1910 the runs were as late as they have been in recent years. The statements in the Commissioner of Fisheries reports for these years also indicate the lateness of the runs during this period. The runs in 1905 and 1906 were exceptional in that 1905 was exceedingly early and 1906 exceedingly late. Following 1910 the runs began to appear earlier in the season each year reaching the earliest occurrence in 1915. From 1916 through 1929 the runs were comparatively early, but in 1930 they began to occur later in the seasons again and in some years have been as late as during the early years of the fishery.

RELATIONSHIP BETWEEN CYCLIC TRENDS IN RELATIVE ABUNDANCE, FISH PER CASE AND TIME OF RUN IN PINK SALMON POPULATIONS

In order to secure a quantitative measure of the relationship between the cyclic trends in the characteristics of the pink salmon as described in Figure 53 coefficients of correlation were calculated be-

tween them. These coefficients are as follows: between relative abundance and fish per case, 0.623 ± 0.091; between relative abundance and time of run, 0.505 ± 0.111; between time of run and fish per case, 0.566 ± 0.101. These coefficients are all highly significant, their probability values in every case being less than 0.01. Although these coefficients are not very great they indicate the existence of a definite quantitative relationship between the factors considered. Therefore, it may be concluded that when the pink salmon populations were large in size the individual fish composing them were usually small and the majority of the fish migrated to the streams late in the season or migratory period. On the other hand, when the populations were small in size the individuals composing them were usually large and the majority of the fish migrated to the streams early in the season.

Owing to the consistent two-year life cycle of the pink salmon they must, of necessity, migrate to the streams at the close of their second year of life regardless of the growth they have attained while in the ocean. In years when the runs of salmon were early and the fish large in size it appears that the environmental conditions in the ocean were conducive to their rapid development and they attained their full growth early in the second summer of their life cycle. In years when the runs were late and the fish small in size it appears that the environmental conditions were not conducive to a rapid development and the salmon remained in the ocean longer in order to attain their full growth but were forced to migrate to the streams before attaining it. It is possible that there are two internal stimuli which may cause the salmon to begin their spawning migration from the ocean, namely, first, the attainment of physical maturity and second the onset of sexual development.

From 1930 to 1933 inclusive a study was made of the physical characters of the pink salmon entering the stream at Olive Cove on Etolin Island in the Sumner Strait area of southeastern Alaska. A counting weir was operated in the stream which provided opportunity to take samples of the fish as they entered the stream at intervals throughout the entire run. A study was made of the physical characters and degree of sexual development of the fish entering the stream in each of the four quarters of the run. The data describing these characteristics of the salmon at Olive Cove are given in Table I. Since the runs in 1930, 1932 and 1933 were comparable both in seasonal time of occurrence and size of fish the data for these years were combined as a unit and compared to the data of the run in 1931.

The data reported in Table I show that the runs in 1930, 1932

and 1933 were later in time of seasonal occurrence than the run in 1931. The fish composing the runs in these years were significantly smaller than those composing the run in 1931 and showed signs of sexual development earlier in the season than did those in 1931. There was no significant difference in the degree of sexual development of the males in the first and second quarters of the runs but

TABLE I—Body Size and State of Sexual Development of Pink Salmon at Olive Cove, Alaska, from 1930 to 1933

Year[1]	Average body length (millimeters)[2]		State of sexual development of males in each quarter of the run (average ratio in percent)[3]			
	Males	Females	First Quarter	Second Quarter	Third Quarter	Fourth Quarter
1931	488.5 ±29.7	482.6 ±16.1	20.38 ±1.08	20.61 ±1.37	20.77 ±1.14	.....
Average of 1930, 1932 and 1933	446.0 ±38.4	445.9 ±26.8	20.20 ±1.01	20.82 ±1.27	21.85 ±1.65	23.55 ±2.12
Statistics of significance	Comparison of above mean values for statistical significance of differences between 1931 and averages of 1930, 1932 and 1933 data[4]					
$\Delta_m \pm \sigma$	42.5 ±3.98	36.7 ±2.88	0.18 ±0.22	0.21 ±0.31	1.08 ±0.44	.....
t	10.7	12.7	0.828	0.672	2.478	.....
n_1	112	95	28	22	17	.....
n_2	337	341	114	81	52	.....
P	<0.01	<0.01	0.40–0.50	0.50–0.60	0.01–0.02	.....

[1] The 1931 data were compared with the averages of the 1930, 1932 and 1933 data combined since the salmon runs in these years were all later in seasonal time of occurrence than the run in 1931. The dates upon which 75 percent of the runs occurred in the Olive Cove area are: 1931, August 11; Average of 1930, 1932 and 1933, August 18.

[2] Body length is measured from back of head to end of scales on the tail.

[3] The head of the males elongates with sexual development and the degree of elongation may be used as a reliable index to the state of sexual maturity. The head length is expressed in terms of the ratio of head length to body length in order to eliminate the size differences in the individual fish. The head length ratio of an immature male is approximately 20 percent and that of a sexually mature male is 24 percent. Owing to unavoidable circumstances the 1931 experiment was discontinued at the end of the third quarter of the run. See Davidson (1935) and Davidson and Shostrom (1936).

[4] For explanation of methods used see R. A. Fisher (1935).

in the third quarter the males in the 1930, 1932 and 1933 runs were significantly further advanced in sexual development than the males of the 1931 run. The males in the fourth quarter of the 1930, 1932 and 1933 runs were sexually mature. Although unavoidable circumstances made it impossible to measure the fish in the fourth quarter of the 1931 run, general observations showed that they all were not sexually mature and ready to spawn. The degree of sexual development in the female salmon was similar to that in the males

but there are no outstanding changes in their structure accompanying their sexual development that may be used as a measure of it.

In 1931 when the run was early and the fish large in size definite indications of sexual development did not appear in the individuals entering the stream until the last quarter of the run. Thus the majority of the fish left the open ocean long before the onset of sexual development. The large size of the fish in this year may be an indication that upon attaining their full physical growth in the ocean they migrated to the stream regardless of their state of sexual development. In 1930, 1932 and 1933, however, when the runs were later and the fish smaller in size definite indications of sexual development began to appear in the individuals entering the stream in the third quarter of the run and was very marked by the fourth quarter. In fact, in these years the majority of the fish entering the stream in the fourth quarter were sexually mature and ready to spawn. In view of the small size of the fish composing the late runs and their advanced state of sexual development it appears that the onset of sexual development stimulated them to begin their spawning migration to the stream regardless of their state of physical maturity. This relationship between the time of the run and the size of the fish in the Sumner Strait area is not peculiar to these four years only but was also characteristic of the runs during the early years of the fishery. From 1896 to 1926, the coefficient of correlation between time of run and size of fish in this area was 0.644 ± 0.117, with a probability value of less than 0.01.

As previously pointed out the data for this study, with the exception of those just discussed, were taken from the records of the fishery in the Clarence Strait area mainly because they were the most complete and covered the longest period of time. This relationship of population size to growth and subsequent time of migration of the salmon was also pronounced in the runs throughout all of southeastern Alaska. Evidence of this was found in the marked similarity of data, insofar as they were available, in the other areas to data of the Clarence Strait area, when compared in point of like periods of time. Although there were years when the abundance of the salmon in one or two areas were considerably below the average for the other areas in the region, nevertheless the size of the salmon and their time of appearance in these areas were comparable to those in the other areas with the greater abundance. In other words, it appears that the growth of the salmon and the seasonal time of their migration in the various areas were influenced more by the abundance of the populations as a whole throughout southeast Alaska rather than by the abundance in the individual areas of the region.

BIOLOGICAL EXPLANATION OF RELATIONSHIP

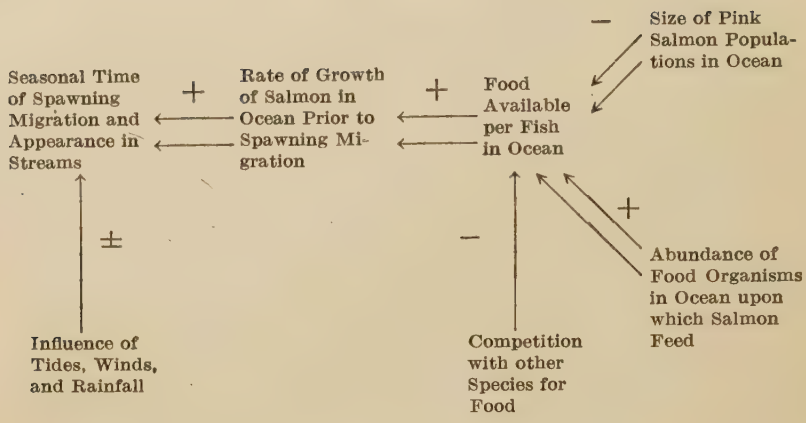
Before discussing the biological explanation underlying this relationship between the size of the pink salmon populations, the size of the individuals composing them and the seasonal time of appearance of the runs, the authors would like to point out that it is being offered merely as a hypothesis. All of the facts thus far available indicate that this explanation is both logical and tenable but if in the future additional facts show that it is not complete or tenable it will be changed accordingly.

The study of the growth and survival of animal populations under both natural and artificial conditions has attracted the attention of biologists for a good many years. Numerous studies have been carried on in this field of work and with few exceptions all point to the conclusion that after a certain limit is reached in the size of an animal population the rate of growth of the individuals composing it decreases. One of the important causes of this decrease in the rate of growth of the individuals, especially in populations of wild animals, is the decrease in the food available per individual which accompanies an increase in their numbers.

As previously stated, although information is not available concerning the size of the pink salmon aggregations in the ocean it is known that the young migrate seaward in schools of immense size and the adults return in similar aggregations. While in the ocean they no doubt feed in schools of varying size as do the king and coho salmon for which there is evidence from the troll fishery. Since the organisms in the ocean upon which the salmon feed tend to swarm as do the salmon it is not entirely amiss to assume that the abundance of the salmon in the ocean brings into play a competition between the individuals for food.

In order to explain how this competition for food, together with other environmental factors, may be responsible for the rate of growth of the individuals and the subsequent time of their spawning migration to the streams, the authors have set up the accompanying word diagram which shows the possible paths of influence of the causal factors involved. In this diagram the double arrows indicate the paths of the most influential factors. The single arrows show the paths of the factors that are as a rule of minor influence but which may at times become paramount in importance. The signs indicate the character of the relationship.

According to this hypothesis the two major factors responsible for the rate of growth of the salmon are namely, first, the size of the pink salmon populations on the feeding grounds in the ocean and, second,


Seasonal Time of Spawning Migration and Appearance in Streams
+
Rate of Growth of Salmon in Ocean Prior to Spawning Migration
+
Food Available per Fish in Ocean
—
Size of Pink Salmon Populations in Ocean
±
Influence of Tides, Winds, and Rainfall
—
Competition with other Species for Food
+
Abundance of Food Organisms in Ocean upon which Salmon Feed

the abundance of the organisms in the ocean upon which the salmon feed. These two factors do not influence the rate of growth of the salmon directly but indirectly through their influence on the food available per individual fish. Furthermore, since these two factors are absolutely independent of each other they may vary together or in opposite directions and may therefore bring about wide fluctuations in the food available per individual salmon, which in turn may bring about similar fluctuations in the rate of growth of the individuals. A minor factor that may influence the food available per pink salmon is the competition these salmon have with other species of fish in the ocean in their search for food. This does not only apply to fish other than salmon, but also to other species of salmon. However, since the pink salmon by far outnumber the other species of salmon in southeastern Alaska, their competition with the other salmon in the ocean may not be of great importance.

The factor that appears to be mainly responsible for the seasonal time of migration of the pink salmon is their rate of growth while in the ocean. Factors of usual minor importance which may influence the time of appearance of the salmon in the streams are tides, winds, and rainfall. The adult pink salmon tend to migrate into the inside channels from the open ocean with the increasing tides. Therefore the occurrence of increasing tides during the migration may tend to speed up the inshore movement of the fish whereas the occurrence of decreasing tides may tend to retard the inshore movement of the fish. Davidson and Christey (1938) have found that offshore and inshore winds have a greater influence on the direction of the migrations than the time of appearance of the runs. The lack of rainfall to maintain the flow of fresh water from the streams along

the shore lines is most effective in retarding the inshore migration of the salmon since they are attracted by fresh water. In years when these three factors have like effects there may be a marked retardation in the time of appearance of the runs in the inside waters and fishery although the salmon may have started their inshore spawning migration from the open ocean early in the season.

In view of the variability the chance combinations of these causal factors may produce in the rate of growth of the salmon and the subsequent time of their spawning migration and appearance in the fishery the authors are of the opinion that the cyclic or long time trend in these characteristics are definitely related to the corresponding trend in the abundance of the salmon but that the yearly deviations from these trends may for the most part be attributed to the influence of the other environmental factors. There have been years when the pink salmon were very abundant, early in time of appearance and the fish comparatively large in size. There have also been years when the runs were small, late in time of appearance and the fish comparatively small in size. These, however, are the exception and not the rule for on the average the size of the fish and their time of appearance may be used at the beginning of each season to roughly predict their abundance.

SUMMARY

In a study of the pink salmon fishery in southeastern Alaska from 1895 to 1940 it was found that:

During the early years of the fishery from 1895 to 1911 there was an abundance of pink salmon in the region which were on the average small in size and late in seasonal time of their spawning migration to the streams.

From 1911 to 1920, during which time the fishery rapidly expanded, the pink salmon declined in abundance, the individual fish increased in size, and the runs appeared earlier in the season.

Following 1921, when the United States Bureau of Fisheries began to introduce more restrictive fishing regulations, the pink salmon increased in numbers. By 1930 they attained their former level of abundance and continued to reproduce near this level through 1940. From 1921 to 1929 the salmon were comparatively large in size and the runs occurred early in the seasons. Following 1929, however, the individuals became comparatively smaller in size, and the runs occurred later in the seasons.

The relationship between these cyclic trends in the characteristics of the pink salmon populations leads to the conclusion that when the

populations are large in size the individuals composing them are usually small and the majority of the fish migrate to the streams late in the season. On the other hand, when the populations are small in size the individuals composing them are usually large and the majority of the fish migrate to the streams early in the season.

The pink salmon have an invariable two year cycle and must of necessity return to the streams to spawn at the close of their second year of life regardless of the growth they have attained while in the ocean. Therefore, a biological explanation of the relationship between population size, growth and seasonal time of the spawning migration of the salmon is hypothesized on the basis of a variable competition between the individual salmon for food in the ocean as their numbers increase or decrease. This in turn directly influences the rate of growth of the salmon and the subsequent time of their spawning migration to the streams.

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NOTES ON THE PHYTOPLANKTON ON GEORGES BANK IN 1940

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In earlier surveys of the phytoplankton of the Gulf of Maine (Bigelow, 1926; Gran, 1933; Braarud, 1934, Bigelow, Lillick, and Sears, 1940; Lillick, 1940) relatively few observations were made on Georges Bank, and the data obtained have not been sufficient to give an accurate picture of the development of the spring flowering in any part of this important bank region. Previous information did, however, suggest that although the spring growth is never as luxuriant on the bank as elsewhere in the gulf, the growth nevertheless continues comparatively rich there throughout the summer (Bigelow, Lillick, and Sears, 1940).

With the hope of learning whether our earlier surmises were correct, samples were collected on five cruises to Georges Bank in 1940, from the latter part of March to the end of June, as a part of the study of the productivity of Georges Bank undertaken by various members of the staff of the Woods Hole Oceanographic Institution (Clarke and Bumpus). These were obtained at certain key stations at the 1, 10, 30, 50, and 80-meter levels, where the depth permitted (Riley, 1941), and at the 1-meter level at certain intervening stations (Figures 54, 55), i. e., at 78 localities in all on the bank and 33 close to the latter but outside the 90-meter contour. These samples were treated in the same manner as those for 1933–1934 (Bigelow, Lillick, and Sears, 1940, p. 151), so that the results of the two surveys should be directly comparable.

In the absence of samples taken prior to mid-March, the data for 1940,[2] fail to give any information 1) of the winter population or 2) of the inception of the spring flowering. However, although we cannot set the precise date for the initiation of the diatom flowering in 1940, this was obviously approaching its height during the

[1] Contribution No. 299.

[2] The original records are on file at the Woods Hole Oceanographic Institution.

TABLE I—Numbers of Diatom Cells Within the 90-Meter Contour on Georges Bank in 1940

Date	Number of stations	Average number per liter	Number of diatom cells as estimated under 0.1 sq. meter of sea surface		
			Average	Maximum	Minimum
March 21–April 1	9	235,000	$1,432 \times 10^6$	$3,195 \times 10^6$	114×10^6
April 17–27	11	432,000	$2,078 \times 10^6$	$11,175 \times 10^6$	106×10^6
May 9–16	10	95,800	669×10^6	$2,629 \times 10^6$	68×10^6
June 1–8	25	19,800	328×10^6	$5,350 \times 10^6$	0
June 19–27	23	17,700	107×10^6	$1,217 \times 10^6$	0

latter part of March (Table I, Figure 54). And it reached its climax sometime about mid-April (Table I, Figure 55), for within the next two weeks, the population had decreased to approximately 1/3 its April value (Table I, Figure 55), continuing to decline to about 1/6 of the peak value by the first week in June and to about 1/20 by the latter part of June (Table I, Figure 55), when the observations were discontinued. In short, we have evidence of an active flowering continuing on Georges Bank for a month, followed by a period of nine weeks—perhaps more—when production was at least moderately active.

Indeed, Georges Bank may yet prove to be among the most productive areas in the Gulf of Maine when we compare diatom counts for the various regions. According to the most recent consideration of this question (Bigelow, Lillick, and Sears, 1940), it is not unusual to find diatoms so thick at the peak of their production that several billion may exist under 0.1 sq. meters of sea surface. However, in most localities this condition persists for a relatively short time and is followed by a period of extreme poverty. For example, the deep offshore stations of the Gulf, which yielded over 3 billion cells "per column" (Bigelow, Lillick, and Sears, 1940, p. 161, Figure 2) in April 1934, became relatively barren within the next month, the population having dwindled to 1/4000 of that existing in April. And even in close proximity to the bank, this same sequence was repeated in 1940, the population being about 1/1000 as great in early June as during the latter part of April[1] (Table II, Figure 55). On the bank, on the contrary, as also in Passamoquoddy Bay, a moderately rich population may persist for several months after the peak of the spring flowering, i. e., we may expect the popula-

[1] The numbers for the immediate vicinity of the bank are perhaps higher than those to be expected in the open basins of the gulf as there is probably some tendency at certain seasons for diatoms to be carried off the bank by the currents, particularly along the southern edge (Bigelow, 1927; Walford, 1938).

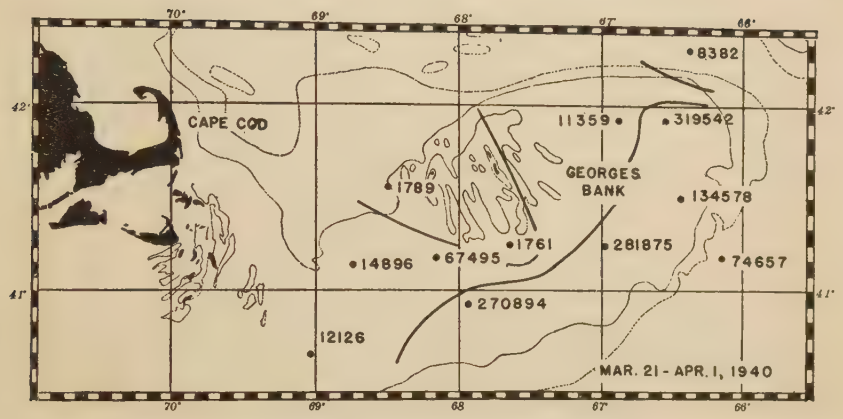

Figure 54. Chart of Georges Bank with numbers of diatom cells in tens of thousands per 0.1 square meter of sea surface. Contours delimit rich and poor areas.

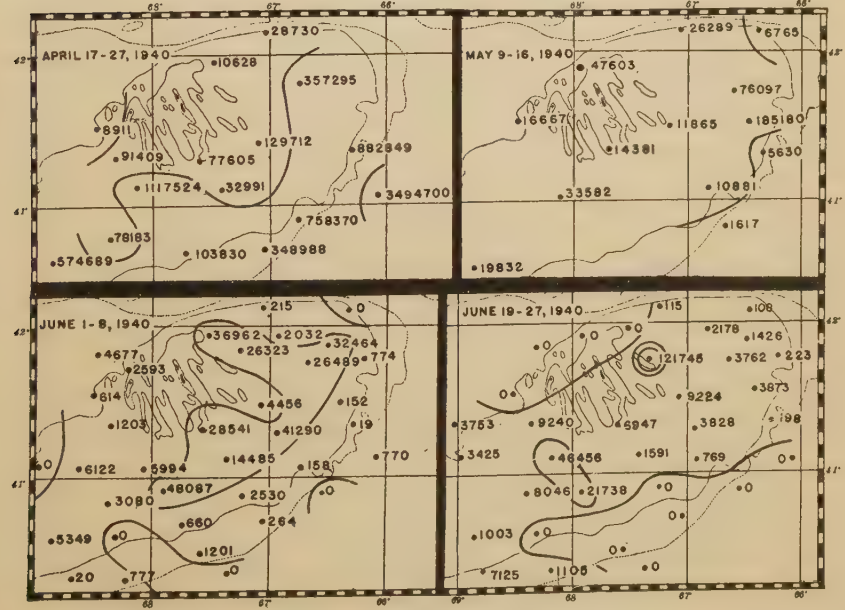

Figure 55. Chart of Georges Bank with numbers of diatom cells in tens of thousands per 0.1 square meter of sea surface. Contours delimit rich and poor areas.

TABLE II—Estimated Numbers of Diatom Cells Outside the 90-Meter Contour of Georges Bank in 1940

Date	Number of stations	Average number per liter	Number of diatom cells as estimated under 0.1 sq. meters of sea surface		
			Average	Maximum	Minimum
Mar. 21–Apr. 1	3	37,950	283×10^6	747×10^6	18×10^6
April 17–27	5	1,250,000	$10{,}988 \times 10^6$	$34{,}947 \times 10^6$	89×10^6
May 9–16	3	10,600	80×10^6	$2{,}629 \times 10^6$	16×10^6
June 1–8	11	1,010	8×10^6	47×10^6	0
June 19–27	11	1,480	12×10^6	38×10^6	0

tion in these localities to average several hundred million cells under each 0.1 sq. meter of sea surface rather than in the thousands. Thus, on the bank, where the counts averaged 2 billion cells at the climax of the flowering (in 1940), the average in late June was still about 107 million or 1/20 the "peak" value. Similarly, in Passamoquoddy Bay, where there is a record (in 1932) of 4 billion "cells per column" at the height of the flowering toward the end of April, in the subsequent period toward the end of June, 600 million cells were found (Bigelow, Lillick, and Sears, 1940, pp. 158, 162, calculated from Gran and Braarud, 1935; see also, Davidson, 1934).

It appears, then, from our survey of Georges Bank in 1940 that the bank is likely to prove to be as productive of phytoplankton as the Fundian region, especially as the scattered observations on the bank in the latter part of the summer show that rich growths regularly occur there at that time (Gran, 1933; Braarud, 1934).

While our 1940 survey shows the bank to be one of the more productive parts of the gulf in the numbers of diatom cells produced per annum, this does not actually answer the important question of whether its productivity in terms of "vegetable matter" is greater than in other parts of the gulf. Indeed, this is a very complex estimate to make, for not only are there differences in the size of the cells of various diatom species and variations in the size of the cells of any given species at different stages in its annual cycle, but also very little is known of their synthetic processes. One index of synthesis used in the survey on the bank is the chlorophyll content of water samples (Riley, 1941), but because there are no corresponding measurements elsewhere in the gulf, we must rely entirely on available information as to the numerical distribution of the species concerned for our estimates of productivity.

On Georges Bank it is doubtful whether Thalassiosira which initiates the spring flowering in most parts of the gulf, is ever as abundant as elsewhere in the gulf (Lillick, 1940, p. 206). Our samples taken the latter part of March support the earlier evidence

in this respect, for the water was dominated by various species of Chaetoceros, especially *Ch. decipiens* and *Ch. debilis* (Table III, Figure 56). These two species were well distributed over the bank, but with some tendency to concentrate over the southeastern half (Figure 57).

Indeed the species, *Ch. debilis* and *Ch. decipiens*, continued to dominate the flora numerically through April and to be as generally

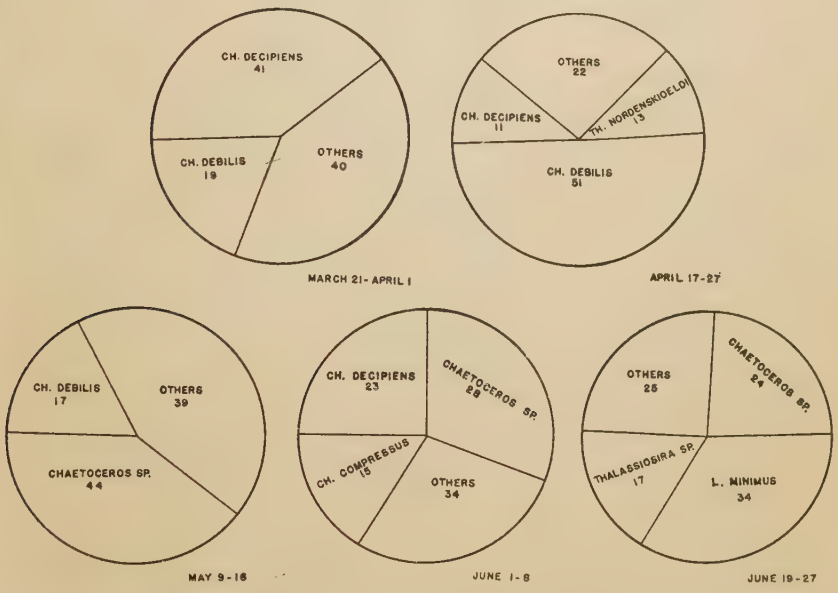

Figure 56. Average percentage composition of the diatom samples taken on Georges Bank.

distributed over the bank (Table III, Figures 56, 57). At the time of the April survey, however, *Thalassiosira Nordenskioeldi* had so increased in abundance that it formed roughly 13% of the total population (as compared with 3% in late March, Table III). It was somewhat more densely distributed over the southeastern portion of the bank, but actually it was thickest outside the 90-meter contour (Figure 58),—presumably having been carried off the bank by the drift of the water (Bigelow, 1927; Walford, 1938).

By mid-May, however, not only had the population of *Th. Nordenskioeldi* again dwindled (now 3% of the total), but also that of both *Ch. decipiens* and *Ch. debilis*. These were almost entirely confined to the bank itself (Figure 57). With the diminution of these

TABLE III—Average Numbers of Diatom Cells per Liter on Each of the Cruises to Georges Bank During 1940[1]

Species	*March*	*April*	*May*	*June 1–8*	*June 19–27*
Asterionella japonica	580	2879	1492	90	X
Chaetoceros atlanticus	2365	4273	1360	360	135
Chaetoceros borealis	3323	4150	689	254	23
Chaetoceros compressus	3983	9172	6888	2904	468
Chaetoceros constrictus	X	90	121	771	1310
Chaetoceros debilis	45238	221517	16686	308	—
Chaetoceros decipiens	95706	46310	5083	4667	791
Chaetoceros laciniosus	X	X	7744	1707	393
Chaetoceros sp.	1720	9129	19569	2212	1249
Chaetoceros spores	X	140	1144	692	665
Coscinodiscus sp.	1359	689	271	172	41
Coscinosira polychorda	419	2391	1139	98	162
Fragillaria sp.	X	X	106	746	X
Guinardia flaccida	X	679	95	X	100
Leptocylindrus danicus	X	25	X	X	204
Leptocylindrus minimus	X	38	X	X	5993
Melosira sulcata	595	1187	12	285	307
Navicula sp.	X	235	257	1376	236
Nitzschia seriata	2492	1143	1779	407	591
Rhizosolenia fragilissima	X	1328	1009	X	89
Rhizosolenia hebatata semispina	249	721	4200	401	20
Thalassionema nitzschioides	1058	1198	324	203	28
Thalassiosira decipiens	3097	11659	2629	466	—
Thalassiosira gravida	805	47	10	1025	242
Thalassiosira hyalina	X	6291	X	X	X
Thalassiosira Nordenskioeldi	7189	55280	3177	119	110
Thalassiosira sp.	98	3825	239	715	2933

[1] X signifies that the species was detected in quantities averaging less than 1 cell per liter while — signifies that the species was not detected on that particular survey.

forms, another Chaetoceros species, *Ch. compressus*, appeared in some abundance over the northeastern portion of the bank (Figure 58).

By early June, the center of abundance for *Ch. compressus* had shifted somewhat to the west and south. And on this survey, with a closer network of stations, it is more obvious that the reduced population of *Ch. decipiens* was chiefly confined to the bank (Figure 58).

By the latter part of June—when the surveys were discontinued—this species was definitely limited to the central part of the bank and the numbers remained comparatively small—only enough to make 4% of the reduced population (Table III, Figure 57). But at this time, *Leptocylindrus minimus* and a small species of Thalassiosira (of doubtful identity) were taken relatively abundantly in roughly this same area (Figures 56, 58).

With this survey of the chief species concerned in the diatom production on Georges Bank, it seemed desirable to justify our contention that the bank is one of the more productive areas (as appears

Figure 57. Chart of Georges Bank with average numbers of representative diatom cells per liter.

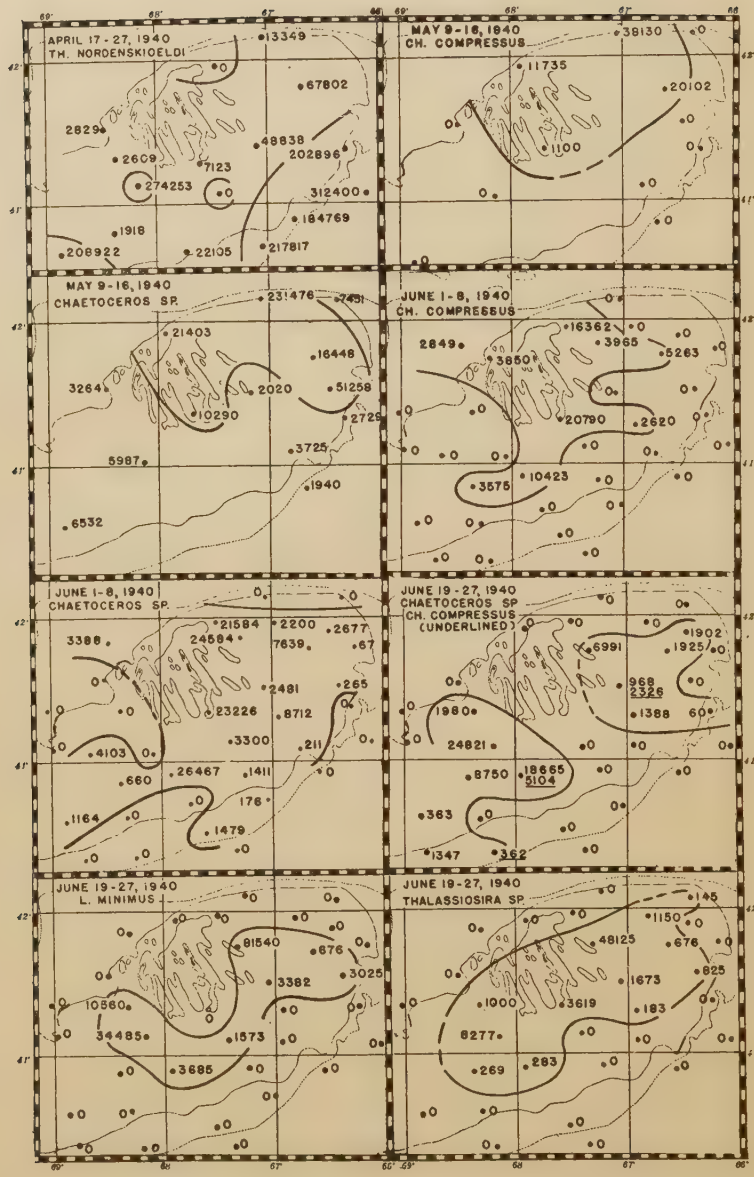

Figure 58. Chart of Georges Bank with average numbers of representative diatom cells per liter.

from a consideration of numbers alone) by a consideration of their bulk,[1] because of the great differences in the size of the species occurring on the bank. Thus, it is obvious that *Chaetoceros decipiens*[2] is many times the bulk of *Leptocylindrus minimus*[3]—I estimate *roughly* 200 times. This would mean that when *Ch. decipiens* dominated the flora toward the peak of the flowering, the organic matter produced by this species alone would perhaps be 3000 times greater than that produced by *L. minimus* when it dominated the plankton toward the end of June—that is, if we are justified in assuming that the production of organic matter by a species is directly proportional to its volume. However, when we consider the bulk of all the more abundant species, it appears that the sizes are so varied at all times that the relative volumes of diatoms do not vary markedly from the relative numbers of diatom cells taken on each cruise (Table IV). Hence we are probably justified in concluding that Georges Bank is among the more productive areas of the gulf.

TABLE IV—Comparison of Relative Volumes[1] and Relative Numbers of Diatom Cells Estimated for each Cruise

Date	*Relative volumes*	*Relative numbers*
March 21–April 1	30	13
April 17–27	28	19
May 9–16	3.9	6
June 1–8	4.4	3
June 19–27	1	1

[1] Estimated from the dimensions given in Gran (1908) and Hustedt (1930) and from Tables I and III.

SUMMARY

The 1940 phytoplankton survey on Georges Bank shows not only that a spring increase takes place but that there is a more prolonged period of diatom abundance than in most parts of the gulf. Furthermore, at the peak of production, the waters surrounding the bank, particularly to the southeast are as rich, if not richer, than the waters on the bank, but later these waters become practically devoid of diatoms (Tables I–II, Figures 54–55).

[1] The volume of a diatom cell may be very roughly calculated from the dimensions given in Gran (1908) or Hustedt (1930).

[2] 12–78 μ wide and perhaps ½ as long (Gran, 1908, p. 74).

[3] 1.5–2.5 μ wide and 40 μ long (Hustedt, 1930, p. 561).

Chaetoceros seems to be the most characteristic genus throughout the spring—a large species, *Ch. decipiens,* being characteristic of the early part of the season and smaller species such as *Ch. debilis, Ch. compressus,* etc., during the latter part of the season, with an exceedingly small species, *Leptocylindrus minimus,* forming as much as 34% by number by late June (Table III, Figure 56).

Taking the size of the species concerned into consideration strengthens the idea that the period of maximum production of "vegetable matter" took place between late March and late April, although the production continued moderate through late June (Table IV). It further indicates that Georges Bank is one of the more productive areas of the gulf.

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